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MODEL DESIGN FOR A BATTLEGROUP INTRANET USING A UAV

by

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March 2002

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MODEL DESIGN FOR A BATTLEGROUP INTRANET USING A UAV

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ABSTRACT

In this thesis the groundwork for an unmanned aerial vehicle (UAV) supporting the communications architecture of a US Naval Battle Group is proposed. The Global Hawk UAV described in detail is used as an example of a viable system. A system using a UAV as a central node in a battle group intranet could enhance the communications within a battle group. The preliminary steps required to demonstrate this concept using a model based on the OPNET software program are defined. The model presented is the one we recommend modifying to research this concept further. Finally, the requirements for transitioning the existing model to one that can test the operational concept proposed in this thesis are given.

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I. INTRODUCTION

A. PURPOSE OF RESEARCH

The purpose of this thesis is to explore the use of a high altitude long operation (HALO) unmanned aerial vehicle (UAV) as a central node in a wireless battle group intranet; the use of an existing model using OPNET is proposed as a testbed which could demonstrate this concept. Current operational communications systems rely on satellite-based equipment that is inflexible, finite, expensive and overloaded. The use of an UAV as a central node in a battle group intranet can address all four of these problems. Specifically the authors wish to answer the following question: “What is a concept of operation for UAVs in order to sustain a tactical local area network in a battle group and how can this be modeled using simulation software?”

In order to do this, several areas of research will be covered. First, we will present a brief overview of some communication systems and their responsibilities. Second, a concept of operations for the use and implementation of a battle group intranet will be offered. Third, details will be given for UAV design and operational requirements, including operating altitudes, endurance, flight control and payloads. Fourth, we will discuss specific equipment design requirements for implementation of a battle group intranet. Fifth, we will show an overview of how existing computer models can be used to assess the feasibility of a battle group intranet. Sixth, we will describe the author’s recommended model. Finally we will present our conclusions and recommendations.

B. BACKGROUND

Communications is the cornerstone to today’s military forces. Without effective communications the navy is limited to the capabilities within the lifelines of the ship. The modern naval engagement no longer involves ship on ship battles within line of sight. New doctrine is being implemented to use Network Centric Warfare as the force multiplier of the future. The navy currently uses satellite and line of sight communications to conduct Network centric operations. This thesis proposes a new use of an existing platform.

C. COMMUNICATION

The Navy by its very nature does not have the ability to use terrestrial networks to communicate between units or with higher command authority. The picture of a ship trailing a phone line behind it as it travels the world oceans is a humorous one. A navy that operates worldwide requires the services of a global communications network. Commanders must be able to communicate between ships, National command centers, and aircraft separated by varying distances. This ability to communicate makes effective command and control possible. That ensures the ability of the commander to use all of the mobile assets sensors to gain a better grasp of events. The global communications network with hundreds of radio and landline circuits supports the fleet. Information affecting the force's mission is exchanged swiftly and accurately throughout every command.

D. LINK SYSTEMS

The navy has been attempting for decades to perfect the transfer of information between platforms, LINK 11, Link 16 and IT-21 are just a few example programs. This transfer of information is seen as a new force multiplier and has been given the title of "Network Centric Warfare."

Network Centric Operations can be broadly described as deriving power from the rapid and robust networking of well-informed, geographically dispersed warfighters. They create overpowering tempo and a precise, agile style of maneuver warfare. Using effects-based operations, the aim is to sustain access and to decisively impact events ashore. Network Centric Operations focus on operational and tactical warfare, but they impact all levels of military activity from the tactical to the strategic. [MAJ99]

The ability to share information in a combat zone is going to be the leading technology concern of future warfighting in the US military. Current information systems rely on UHF Line-of-sight (LOS) or Satellite communications to transport data. The new concept of Network Centric Operations is beginning to overtax current transmission mediums.

E. NAVY STOVE PIPES

Telecommunications used by US Naval Forces continues to migrate toward Internet Protocol (IP) based technology. IT-21 focuses on modernizing local area networks (LAN) afloat and LANs or wide area networks ashore (WAN). Intra-Task Force network connectivity is one area of the IT-21 concept that is not being full utilized

IT-21 configured ships use Satellite Communications (SATCOM) to communicate information with other ships or shore stations not in LOS of each other. Shipboard C4I systems use SATCOM as their access point to these networks. A simplified view of this is the afloat user's information starts by transmitting military-related IP datagrams from the ship to the nearest telecommunications facility ashore via geo-synchronous satellite. The ashore station then routes the datagram to its' destination. When the destination location is not accessible via landline such as a ship in the battle group, the telecommunications station places the datagram back into the queue for rebroadcast over SHF SATCOM to the receiving unit. [Bud01]

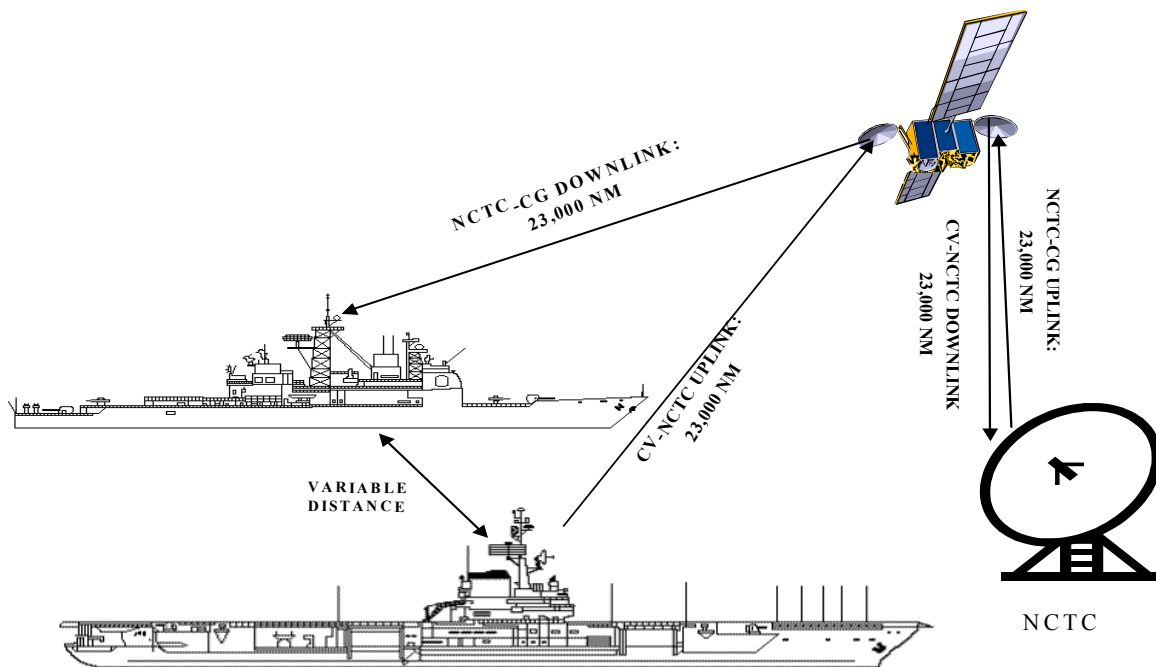


Figure 1 Simplified drawing of Current Intra-Task Force Network Architecture

[From: BUD01]

The network scenario described is efficient only if the variable distance between units in figure 1 is greater than the radio horizon. If that variable distance is less than the radio horizon then the datagram traveled 92,000 miles linearly to traverse 50-100 miles laterally. The 'local' data competes for expensive 'long-distance' system time. As information demand increases, so does the value of the bandwidth on the SHF SATCOM. In the best of all possible worlds, the answer would be another system dedicated to Task Force Internetworking.

F. WHY NOT A SATELLITE?

A geosynchronous satellite operates at approximately 22,500 miles above the earth. This is the altitude that a satellite must maintain to provide continuous coverage of a specific geographic area, approximately 1/3 of the earth. This altitude allows a user to have continuous access but at some costs. If a lower altitude is used, continuous coverage is not possible without increasing the number of satellites in the constellation. However, the power required to reach a satellite on geosynchronous orbit, 22,500 miles, is much greater than the power required to reach a UAV at 120 miles slant range.

The footprint of geosynchronous satellites provides constant 24 hour a day access. One of the drawbacks to this is there is a limited number of frequencies available in the Electromagnetic spectrum. A UAV has a smaller "footprint" so frequency reuse through geographic separation is an added benefit. An example of this is Two battle groups 1000 nm apart can see a GEO SAT. They both use the same frequencies to communicate through the satellite. This causes collisions of information going through the same pipe to talk to other members of the same battle group. If a UAV were used as a communications platform the lower power required for a signal to reach a UAV would allow the battle groups to use the same frequencies without competing for spectrum use, simply because they could not detect the other battle groups signals.

G. UAVS

The concept of each battle group having its own dedicated group of UAV communication platforms to provide 24/7 connectivity is one solution. The Navy and the Air Force have tentative plans to purchase approximately 100 long-range Global Hawk UAV's. [DN 02] Because the Navy is already looking at purchasing these airframes we

have used the Global Hawk as a baseline platform from around which to build a battle group intranet.

H. MODELING AND SIMULATION

The use of models to test proposals before their implementation is one cost effective solution to prove a concept. Of course there will always be unforeseen events that occur, but experimenting can quash or buttress a proposal because of the insight gained through simulation. In this case, a US Navy battle group, a Global Hawk UAV, all of the networking components, and many other factors are too costly to *physically* experiment with, without first having better understanding of how various systems should be designed. Simulation and modeling coupled with physical experimentation are necessary to improve war-fighting capabilities.

This thesis assesses the initial requirements, using simulation and modeling software by Optimum Network Performance (OPNET) Technologies. The software recommendation for further evaluation will be described in Chapter VI.

I. SCOPE AND METHODOLOGY

Initially, the authors' intended to create a model representing a 10-ship battle group with one UAV as a network node. We will present a UAV system and a concept of operation. Also, modeling and simulation is presented to show that it is an effective tool in evaluating the benefits of proposed systems. Finally, we evaluate an existing model that can serve as a foundation for further research in order to demonstrate the feasibility of the new system.

The authors decided to use a pre-designed model that could later be modified to emulate a UAV Battle group intranet. The model presented in chapter six uses two ground stations in Brazil and Algeria, which can be looked at as stationary ships. The UAV portion of the model is represented by two low earth orbit (LEO) Satellites. The data that can be extrapolated from this model can be directly applied to the UAV problem and the authors will show how the results will be beneficial to further research.

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II. CONCEPT OF OPERATIONS

A. INTRODUCTION

The current revolution in military affairs is based on information. The need for this information has created systems and concepts of warfare based on obtaining and distributing information. This chapter has been divided into five parts to define and identify some of the operating concepts affecting the use of the HAHE UAV.

The Navy is seeking to maintain its technological edge in warfare today. Many of the weapons systems being obtained by foreign entities are becoming equal in their capability to that of American systems. Additionally, American weapons systems are being sold to other countries. This equality in armaments is causing the United States to look for other ways to gain an advantage. This quest, continue to hold advantage over potential adversaries, has led to revolutions in military affairs and unintentional change.

Satellites are expensive to build and launch. This cost is not just measured in dollars. If something goes wrong during the launch or while on orbit there is no way to repair it. The shuttle only travels to approximately 350 miles above the earth. It does not have the range to retrieve a Geosynchronous satellite. If a problem should occur there is no current way to repair it on orbit. The satellite becomes a liability if units are depending on it for connectivity. Current trends in technology also limit the usefulness of legacy systems because of Moores Law. The usefulness of a satellite is only a few years before new technology overtakes the embedded circuitry. With no way to upgrade systems a satellite is left in the past. The advantage a UAV brings to the table is that it can be repaired and upgraded with new technology constantly like the B-52, which has a service life already at 50 years.

B. THE NEXT STEP

The nuclear bomb was briefly considered to be the ultimate revolution in warfare. The use of nuclear weapons is no panacea as a force multiplier. The United States and the former Soviet Union, realized that the nuclear weapon was not the final solution. The fall of the Soviet Union once seen as the ultimate victory has opened a Pandora's box of smaller globally dispersed areas of concern. These smaller conflicts are between

groups separated by many different reasons. Many of these warring factions have been given access to modern sophisticated weaponry. This proliferation of technologically advanced weapon and information systems has caused a re-assessment by the United States in the quest to retain the edge in relative power.

C. REMOVING AMBIGUITY

Carl von Clausewitz's explanation of the "fog of war" is the best example of the next great military challenge. Removing the ambiguity of who, what, where and [OWE00] when is the focus of this quest for information technology. Network centric operations are the new path the United States is attempting to travel. This new force multiplier is being heralded as the best, non-nuclear, way to defeat our next adversary. The concept has been embraced by all four services in various ways in an effort to achieve the best solution for their service. This vision has been presented for the Navy in a new paper *NETWORK CENTRIC OPERATIONS A Capstone concept for Naval Operations in the Information Age*.

The Capstone Concept for Network Centric Operations articulates the United States Navy's path in transformation to *Network Centric Operations*. The Concept applies the defining tenets of joint and naval warfare to network-centric war fighting and provides a vision of the new capabilities we must achieve. The improvements in our ability to quickly attain and sustain global access as a result of this transformation are critical to enabling our naval forces to decisively influence future events at sea and ashore – *Anytime, Anywhere*.

[NWC01]

This paper communicates the Navy's vision on the importance of using information to amplify the combat power of the war fighter. The plan is for US forces to use superior knowledge to exploit weakness and concentrate combat power. One of the pillars of this concept is assured access. The use of a HAHE UAV is one way to support this concept.

D. CURRENT SYSTEMS

The concept of sharing tactical operational and strategic information is not new. Its roots are embedded in the Tactical Data Link systems. The Navy created LINK 11 and shares with the Air Force today, Link 16. Link 16 is recognized under two other names

as well, Tadi-J, and JTIDS. All of these systems use line of sight to relay data and are dependant on manned aircraft or satellite to relay the information over the horizon. There are several problems with these systems. The equipment involved is too heavy and costly to be placed on smaller ships because of the large satellite dish required. Distance is limited to line of sight or by the use of satellites.

The satellite has been viewed as the preferred way to communicate over long distances for ships. But there are several drawbacks to satellites. To provide continuous information flow the satellite must be in geosynchronous orbit at 22,500 miles above the earth. This distance presents a number of problems to be introduced, such as time delay, needed power and frequency reuse capability.

The position of a satellite is easily determined with a stopwatch, sky map, personal computer and (optionally) binoculars. [THO95] The ease at which this targeting data can be determined makes the task of using an anti-satellite weapon(ASAT) or electromagnetic pulse (EMP) much simpler. The possibility of a rogue nation using a nuclear warhead as an anti-satellite weapon (ASAT) is a concern. Not only would the satellites in the blast zone be destroyed, but for up to six months following the detonation, the outer Van Allen belt would contain some amplified radiation. This radiation could quickly degrade or eliminate most unhardened satellites in low earth orbit. The effects to Geosynchronous satellites would probably not be as severe but it would have some effects. [THO95]

Low earth orbit satellites can be retrieved by the shuttle system. But to provide total access a low earth orbit system requires large numbers of satellites to provide worldwide-uninterrupted coverage. At an altitude on only a few hundred miles these satellites only have an overhead time of a few minutes until use must be passed on to the next satellite coming into view. The process of transferring information at high data rates to and from the satellite becomes cumbersome.

The current systems that do use satellites have used up much of the bandwidth capability that they do provide. These systems are already crowded and are becoming more so every day. The solution for the battle group is to have its own “geosynchronous”

platform that is cheap, maintainable and only serves the battle group. This solution is the Unmanned Aerial Vehicle Airborne Communications Node (UAV ACN).

E. TOPOLOGY OF THE AIRBORNE NETWORKING NODE

With current systems some ships cannot communicate with others without using the satellite because of distance. Only the carrier and large deck amphibious ships have wideband capability. Other ships in the battle group require similar information but the data transfer is so slow that they tie up circuits receiving mission critical information. The time it takes to download an Air Tasking Order (ATO) or Tomahawk Mission Data Update (MDU) can be hours depending on the size of the file and the bandwidth available. This inefficient use of a narrowband system could be a crucial vulnerability in future battles.

The 21st –century battle group consists of nominally 10 ships made up of DDG, CG, DDX, CVN, and other Allied ships. An example of the dispersion of a typical battle group is seen in figure 2.

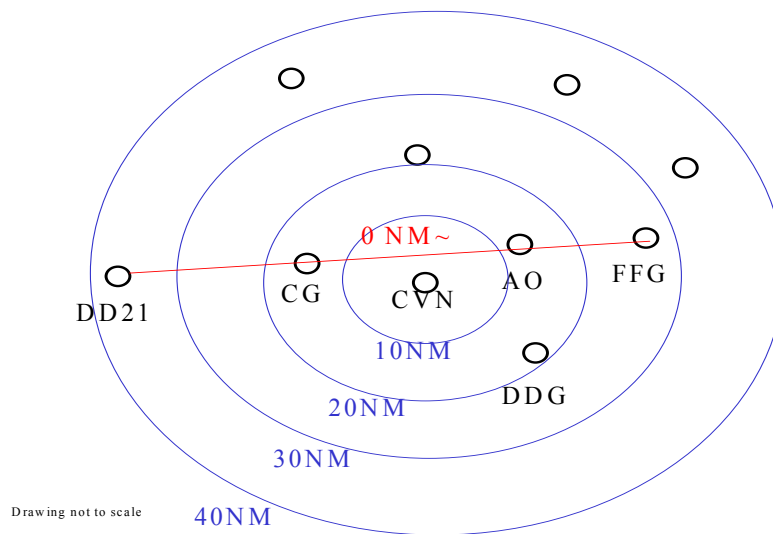
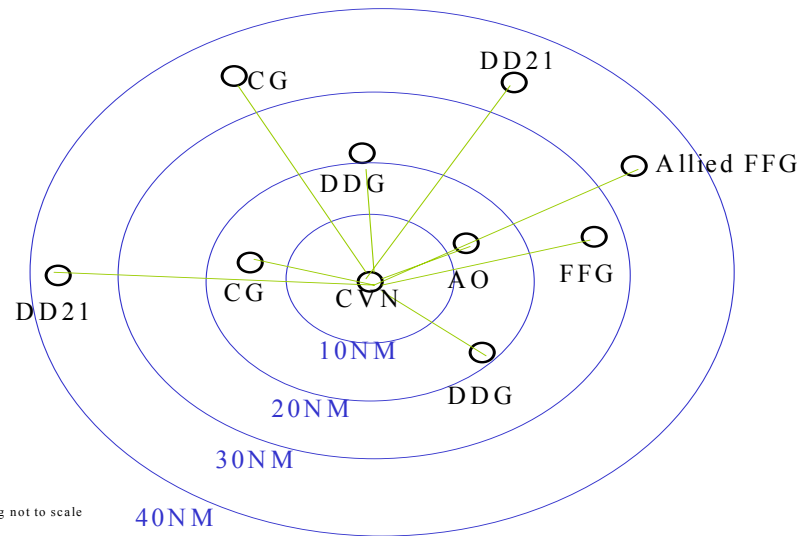


Figure 2 Battle group Screen

The notional ranges between ships present a valid dispersion of today's fleet. UHF radio communications are good for about 30 Nautical Miles (nm). This range is affected by atmospheric conditions on an hourly basis. Communication ranges can

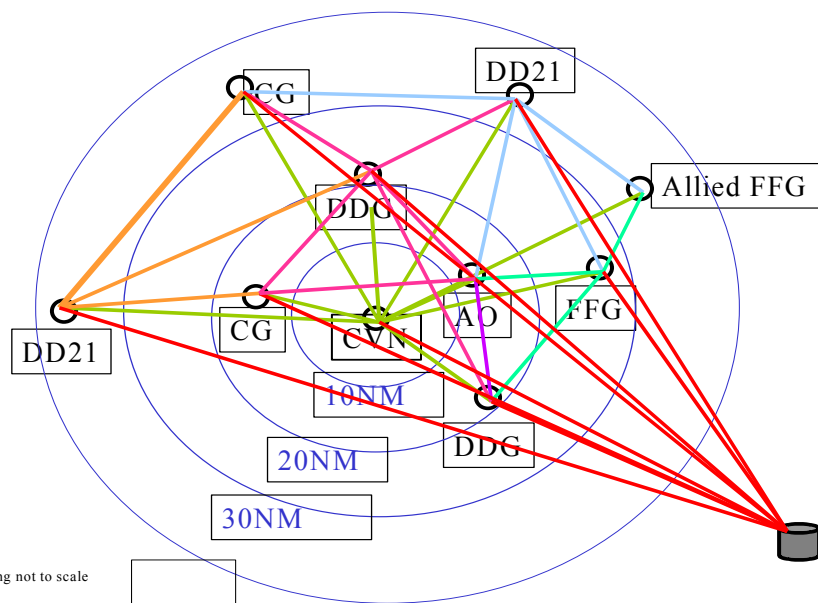
shorten to as little as 20 nm or grow too as great as 100 nm with gaps in coverage in-



between units.

Figure 3 Battle group/CV Connectivity

The carrier is usually the center of the formation and has most opportunity for connectivity between other units. This is most easily viewed as a hub network as seen in



figures 3.

Figure 4 Satellite/CV/Satellite Connectivity

Figure 4 depicts communications between other ships in and out of range for UHF Line of Sight (LOS). If units are unable to use LOS a satellite must be used to bridge the gap. Some Allied ships do not have the ability to use our data because of lack of satellite access.

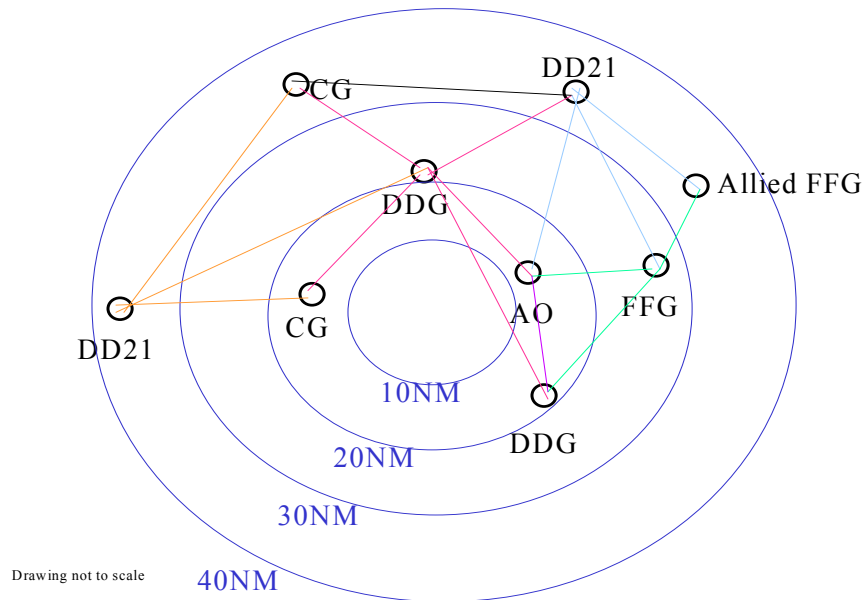


Figure 5 Battle group Connectivity Without CV

Remove move the Carrier, Figure 5, and a large portion of the connectivity is lost. Hops have to be made via satellite or through other ships not capable of handling the

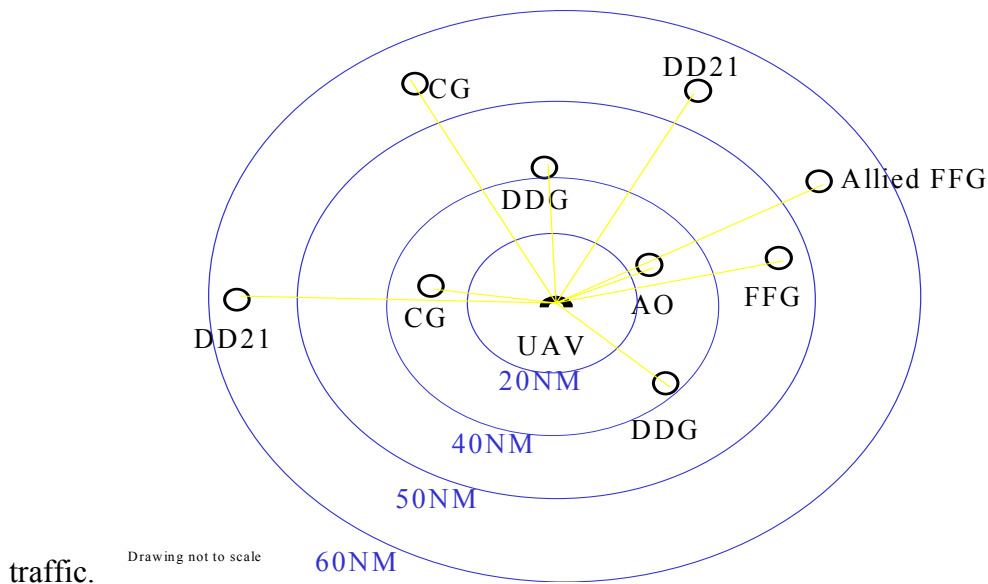


Figure 6 Battle group Connectivity with UAV

With a HAHE UAV as the central node, information can flow between units with greater ease and volume, as seen in Figure 6. The high altitude of the UAV also allows greater connectivity at longer ranges with out using a satellite.

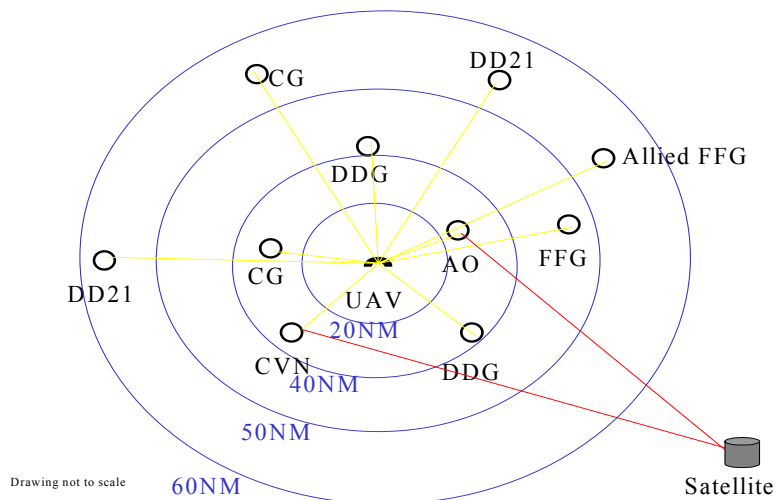


Figure 7 Full Battle group Connectivity

The capacity of a UAV to directly access the secure internet protocol routed network (SIPRNET) or non-secure protocol routed network (NIPRNET) is limited to a

T-1 line because of the size of satellite dishes on destroyers and frigates. If the Carrier is brought back in to the link it currently uses a large diameter satellite antenna to provide rapid access to shore facilities. Global Hawk UAV has an antenna capable of connecting with a satellite to provide reduced connectivity. The Carrier also has the room to act as a cache server for information. High bandwidth information such as weather photos and intelligence briefings can be stored on a cache server to reduce the amount of reach back required. Many of the ships clog the satellite channels with requests for the same information. The fleet oilers also have the additional deck space that might provide the same service as a carrier. While an AO is not available constantly due to the nature of their mission it could be used to fill in.

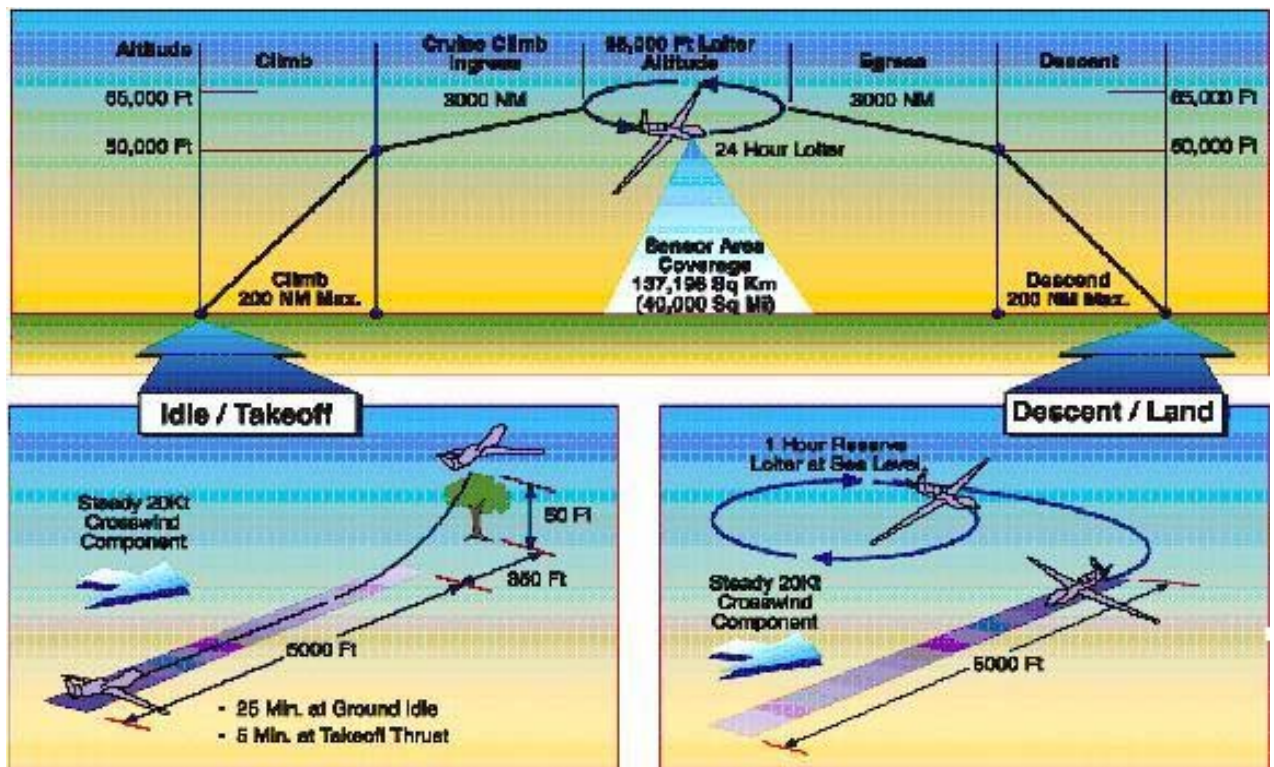


Figure 8 Global hawk Mission Profile

[From: USAF98]

The Global hawk can offer the range and the endurance required by a battle group commander to provide continuous access to information from all battle group resources. The mission profile depicted in Figure 7 is a typical flight plan a HAE UAV would take to and from station. The sensor area coverage depicted is for the EO/IR sensor with a

radius of 112 miles. Comparable or greater coverage areas might be achieved with a communications package.

Once on station the UAV would be repositioned via inputs from the battle group commander as needed. Defensive measures are discussed in Chapter III.

F. SCENARIO

An example for the implementation of a HAHE UAV ACN is the 1999 conflict in Kosovo. The *Theodore Roosevelt* Battle group was dispatched as part of a normal deployment to relieve the *Enterprise* Battle group for combat operations in the Kosovo AOR. The battle group did not steam together in a traditional formation while conducting operations. The Adriatic was considered too small for the *USS Theodore Roosevelt* to conduct operations with other NATO carriers in the area. The possible submarine threat also made it preferable to operate the carrier in an area near the heel of Italy. There the carrier could operate freely. The Air Warfare coordinator, Red Crown, was located on an Aegis cruiser in the middle of the Adriatic off the coast of the Former Yugoslavia approximately 100 miles from the carrier. The other units of the CVBG were located around the AOR.



Figure 9 Adriatic Op Area

[From: MAP02]

Red Crown was able to use UHF for radio communications between herself and the CVN but could not communicate with other units as close as 40 NM away. The long-range communication was due to atmospheric ducting, which cannot be relied on as a communication path. All other communications were done through satellite or through the USAF E-3 AWACS. If a HAHE UAV ACN like our model had been available it could have provided communication connectivity in the footprint as shown in Figure 10.



Figure 10 Envisioned UAV Coverage

[From: MAP02]

A detachment of four aircraft could have been stationed at the NATO base in Brindisi. From an operating position over the Ionian Sea a HAHE UAV could have provided connectivity to all units in the area including some of the NATO units. The ability to use a forward base so close to the battle area would have increased on station time. The probability that future conflicts will not operate in the close proximity to a friendly base is the reason why the Global hawk model with a 3000 NM range is used. There is a much higher probability for a friendly base within 3000 NM.

G. FUTURE APPLICATIONS

Other uses for a HAHE UAV ACN are easily implemented. The Navy is actively pursuing the VTUAV concept. Data from this platform will be able to be simultaneously broadcast to the ACN for use by all of the units in the battle group. A HAHE UAV could be used as a bridge to increase the range that CEC units could communicate with each other, current CEC airborne applications for the E-2C weigh 700 pounds or in cooperation with land based Army units providing theater ballistic missile defense. In areas where the Army has radar information, it could be passed to a shooter on the water.

It could also be the central node for additional UAVs. A possible ASW version for the Global hawk is in the design phase as a replacement of the P-3. The ASW warfare commander could use this to control a squadron of ASW UAVs to detect and prosecute submarine contacts. Submarines could use this to assist them as an off ship sensor. UAVs could scour an area ahead of a submarine and report their finding back to the sub or to a convoy. Connecting with the HAHE UAV in short bursts for target updates and new search patterns it would greatly enhance the capability of the submarine.

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III. BUILDING BLOCKS OF UAV BASED NETWORK

A. INTRODUCTION

The Unmanned Aerial Vehicle (UAV) can trace its history back to the Vietnam War with the use of the AQM-34 as a reconnaissance drone. In following years the United States realized a growing need for tactical, inexpensive over the horizon targeting capability. The Pioneer UAV initially fulfilled this vision. During Desert Storm the Pioneer proved the concept and value of the UAV. [MAJ99] Most recently the UAV has proved itself in Kosovo and Afghanistan. The UAV's were critical to the reconnaissance mission in Kosovo. Several UAV were lost to enemy action. These losses were offset, by the relatively low cost when compared to a manned aircraft, and because there was no pilot to rescue further endangering personnel. [COH00]



Figure 11 BQM-145A,

[From: FAS01]

The acceptance of the UAV concept has gained a foothold and is growing. With the reduction in military force size and budget and increase in global requirements the US military began to look at ways to increase their technical advantage and minimize risk to personnel. One of the force multipliers chosen is the UAV.



Figure 12 Pioneer UAV

[From: FAS01]

The Navy's new focus on Network Centric Warfare has created a need for real-time intelligence and imagery not available from national assets. The test for the Navy is to provide products and information that is current and readily accessible to the decision makers on the sea. This requirement for information has been the driving force in recent UAV design. [MAJ99]

Current UAV design focuses on its use in a sensor to shooter concept. That means most current UAVs primary missions are reconnaissance. The value of this information to the user has greatly enhanced the capabilities of the fleet. The UAV has the potential to increase capabilities beyond this task. The use of a UAV as a communications platform is one of those increased capabilities. If the UAV is to grow beyond its initial concept a list of performance requirements must be decided on.

B. TYPES OF UAV

There are several types of UAV currently in Research and Development and operating in the military. The different types are classified into three areas, Tier I, II, and III. Tier I UAVs are designed to be quick reaction type aircraft such as the General Atomics *Gnat 750*. The Tier I is designed for tactical missions launched from ships or on the battlefield. Tier II are designated as medium altitude endurance aircraft such as the

General Atomics *Predator* and *Global Hawk*. Tier III is designated as a high altitude low observable aircraft such as the Lockheed Martin *Dark Star*. [FAS01]



Figure 13 GNAT 750

[From: FAS01]



Figure 14 Predator RQ-1

[From: FAS01]

C. UAV AS A NETWORK NODE

For the UAV to function as a central node in a battle group intranet several factors have to be looked at, including but not limited to loiter time, altitude, and payload.

One of the most important requirements for a local area network to operate effectively is access. This requirement dictates that a UAV must be available 24 hours a day with minimum disruption in service, similar to a geo-synchronous satellite. This requirement for constant access can be solved in two ways, multiple aircraft with short loiter times or fewer UAVs with longer loiter times.

For the purposes of this thesis the authors have made some assumptions about the operating environment. For illustration purposes the authors will use a *Predator* with a shorter loiter time and the *Global Hawk* as the UAV with a long loiter time as the model aircraft. An assumption is being made that a friendly airbase within 400 miles is available, this is a requirement for the *Predator* not the *Global Hawk* and should be looked at as another restriction of short loiter time UAVs.

Table 1 Comparison of Global hawk and Predator

	<i>GLOBAL HAWK</i>	<i>PREDATOR</i>
Contractor	Northrop Grumman Integrated Systems	General Atomics Aeronautical Systems Inc.
Power Plant	1 Alison model AE3007H turbofan	RQ-1B 914 four cylinder turbo charged engine producing 105 horsepower
Length	44feet (13.5 meters)	27 feet (8.22 meters)
Height	15 feet (4.6 meters)	6.9 feet (2.1 meters)
Weight	9,200 pounds(3,680 Kilos)empty, 25,600 pounds(9,846 Kilos)gross	950 pounds (431 Kilos) empty, 2,250 pounds (1,020.6 kilos) gross
Wingspan	116 feet (35.4 meters)	48.7 feet (14.8 meters)
Speed	Cruise 343Knots,	Cruise 70 Knots, 120 knots max
Range	Ferry 13,500nm, Mission 3000 nm with 30 hours on station	400 nm with 16 hours on station time

Ceiling	65,000 feet (19, 810 meters)	25000 feet (7,620 meters)
Fuel Capacity	14,500 pounds (5,800 Kilos)	665 pounds (204.1 Kilos)
Payload	2000 pounds (907.2 kilos)	450 pounds (204.1 kilos)
System Cost	\$15 Million per airframe	\$3.7 Million per airframe

[After: ONR00, USA01]

Multiple aircraft present different problems in the complexity of keeping a UAV on station at all times. Using a *Predator* with an on station time of 16 hours as an example. In a given day there is a requirement for two aircraft to be on station during a 24-hour period. With two aircraft the number of landing and takeoffs is doubled and the chance for damage during this evolution is increased. With multiple aircraft the problem of switching the transfer of data from the oncoming aircraft to the off going aircraft as a possible point of failure is increased.

Each additional aircraft increases the maintenance that must be performed, which might increase the ground crew requirements based on maintenance hours per flight hour. Assuming a three-day cycle two aircraft would be able to maintain station if a forward operating base was close enough to the fleet. But assuming a 400 mile trip from a forward ground base to the battle group there would be only be enough time to provide fuel and the most rudimentary maintenance of the UAV before it would be required to relieve the other aircraft. An advantage to multiple aircraft is the redundancy provided if one should fail.

The advantages of a UAV with long loiter time are constant service. Fewer handoffs of data to different platforms mean fewer chances for malfunctions. Longer loiter times allow down time for aircraft between missions providing the ability for maintenance. A global hawk could be back to its base in 90 minutes and have almost 20 hours of down time with two aircraft.

One way to provide continuous service would be a land based squadron of four global hawks to provide 24-hour coverage and maintainability. This number of aircraft

allows flexibility in maintenance and for the aircraft to have a bigger window to arrive on station to provide continuous coverage.

D. HIGH ALTITUDE

The HALE UAV cannot provide the same coverage as a satellite. To be effective a UAV used as an intermediate node in a battle group intranet would have to be located at a high altitude to provide a footprint large enough to allow a tactically deployed battle group to achieve continuous connectivity.

E. CONTROL SYSTEMS

UAVs can be operated using either control signals from a remote location (air or surface), or pre-programmed instructions, providing automatic or autonomous control. To control the UAVs attitude, airspeed and height, on-board sensors are required to collect and relay information either to the remote controller or the on-board FCS. While some flying skills are required to manually and remotely control most UAVs effectively, some vehicles employ a flight control system (FCS), which does not require the controller to have flying skills. Although the controller launches and recovers the vehicle, flight control during the mission is accomplished by the on-board FCS and navigation system. Although autonomously controlled vehicles are capable of performing their full mission profiles from take-off to landing without human intervention, changes can generally be made to mission profiles during flight by transmitting data from a remote location. For a UAV to provide continuous coverage to a battle group, in-flight course corrections would be sent to the aircraft by a ship in the battle group. [LAX96]

F. FLIGHT CONTROL SYSTEM

Like a manned aircraft, a UAV is dependent on a ground support infrastructure that varies in accordance with the comprehensiveness and complexity of the mission. Some UAVs use a Ground Control System (GCS) for flight control, while autonomous UAVs require a GCS only for mission monitoring and changes. A mission support system (MSS) will also be required for planning and for receiving mission data transmitted from the vehicle. Sensors and weapons can also be controlled from the GCS. This support infrastructure adds considerably to the overall system cost, complexity, and to the amount of equipment transported as part of deploying UAVs.

An important recognition is that UAV s retain human control, albeit from outside, rather than from on-board the vehicle. Thus the operator is removed from the cockpit but not from the mission. This is an important feature not always recognized by those who would criticize the use of UAVs, even for basic reconnaissance missions. [MAJ99]

The Off ice of Naval Research (ONR) has identified a classification scheme for the combat UAV program, which shows the levels of human interaction with a UAV.

Table 2 UAV Classification System

Level	Name	Description
0	Human Operated	All activity with in the system is the direct result of human-initiated control inputs. The system has no autonomous control of its environment, although it may have information-only responses to sensed data.
1	Human Assisted	The system can perform the activity in parallel with human input, acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input.
2	Human Delegated	The system can perform limited control activity on a delegated basis. This level encompasses automatic flight controls, engine controls and other low level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operations
3	Human Supervised	The system can perform a wide variety of activities given top-level permissions or direction by a human. The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviors that are not within the scope of its current directed tasks.
4	Mixed Initiative	Both the human and the system can imitate behaviors based on sensed data. The system can coordinate its behavior with the human's behavior both explicitly and implicitly. The human can understand the behaviors of the system in the same

		way he understands his own behaviors. A variety of means are provided to regulate the authority of the system with respect to human operators.
5	Fully Autonomous	The system requires no human intervention to perform any of its designed activities across all planned ranges of environmental conditions.

[From: ONR00]

A UAV operating with a battle group would have to have some human interaction to adjust its placement in the airspace over a battle group. This may include adjustment of altitude or size and placement of the UAVs orbit. Navigation and guidance systems are essential for UAVs operating out of line-of-sight and having limited or no human input after the start of the mission. Simple UAVs may be guided either directly by the controller maintaining visual contact or indirectly using a visual display relayed from the UAV to the controller by an on-board sensor. The guidance system may also be linked to the payload to relay instructions for the UAVs capability. Remote piloted vehicles (RPV) require a ground control station positioning system (GPS), long-range aircraft navigation systems and terrain matching, possibly linked into FCS activation. For UAVs dependent on instructions relayed from a remote station, the guidance may be that required to allow the vehicle to fly from waypoint to waypoint. Vehicles requiring extreme guidance accuracy for autonomous take-offs and landings can use a Differential GPS. This modified GPS system is based on a ground station at a known datum providing differential corrections to the on-board GPS receiver for more accurate guidance accuracy on the order of two meters can be achieved within a radius of approximately 800 kilometers of the reference receiver. UAVs employing autonomous or part autonomous control will have a mission computer as part of the overall navigation and guidance system.

G. TACTICAL CONTROL SYSTEM

The Tactical Control System (TCS) is a subsystem of the Navy's new Vertical Takeoff UAV (VTUAV). It is the software, firmware, hardware, and the extra Ground Support Equipment (GSE) (antennae, cabling, etc.) necessary for Level 5 control of Tier I and Tier II UAVs. Current tactical UAV systems were initially procured using the Advanced Concept Technology Demonstration (ACTD) acquisition approach. Software

and data links of current tactical UAV systems are not compatible or interoperable. Their ground control stations do not have the required capabilities or the architectural room for growth to satisfy all the Joint Service operational requirements. Each UAV ground control system is unique and not interoperable with other UAV ground control systems. The TCS program provides joint war fighter commanders with interoperable and scalable command, control, communications and data dissemination systems for the family of present and future UAVs. TCS eliminates the current approach of a unique control system for each type of UAV. TCS is a subsystem of VTUAV, and will be interoperable with all UAVs, including Predator, Outrider, and Pioneer, and will be capable of disseminating critical data for planning, targeting, and combat assessment to support Joint services at multiple echelons. [MAJ99]

The use of TCS in the VTUAV program simplifies some aspects of shipboard control of a HAHE UAV. The ability of a common control system which to control both types of UAV will greatly enhance the capability of the ship to control a HAHE UAV. The use of the same crewmember for both missions also reduces the manning requirement.



Figure 15 TCS Station

[From: FAS01]

The TCS is compact enough to fit onto the back of HUMMV, including two control stations. The dual use of the same equipment for the VTUAV eliminates redundancy in shipboard equipment as well.

TCS is just as likely to be targeted for jamming as any other system involving communication links. These threats include, electronic warfare, information warfare and physical destruction. When the UAV GCS is transmitting the major threat includes direction finding and jamming. Adversaries could home in on the signals and locate its source. [JFC00] These same electronic problems are common to the HAHE UAVs primary mission and will be addressed in chapter IV.

TCS is being designed to be a comprehensive system for all Tiers of UAV. Some of the functionality the system will provide for a HAHE UAV Communication node is listed here:

- a. TCS Display the location and systems status of the GCS and location of the UAV.
- b. A display of the coverage footprint on a moving map to facilitate the best coverage location for the UAV with respect to the battle group.
- c. Receipt, processing, formatting, storage, retrieval of onboard flight and weather data.
- d. The ability to pass control of the UAV from one TCS-compliant GCS to another.
- e. Provide caution/warning to the operator when the UAV detects a fault.

[JFC00]

The drawback in using a Global Hawk airframe is that it does not currently use the TCS system for in-flight control, which is being required for all future UAVs. The TCS system should be incorporated into any future design.

H. LAUNCH AND RECOVERY

A variety of systems exist for launching and recovering UAVs. Launch systems can be fixed or mobile and be as simple as bungee or pneumatic powered catapults to

semi- prepared or fully paved runways, depending on the size and performance of the UAV. Large UAVs designed for medium to low altitude such as those from the Teledyne Ryan Aeronautical (TRA) Firebee family can be air launched from aircraft such as the C-130 while smaller vehicles, such as the TRA BQM-145A Medium Range UAV can be air launched from the F/A-18 Hornet. Recovery can be by parachute, either to the ground or for mid-air retrieval using a helicopter fitted with the US developed mid-air recovery system (MARS). Smaller UAVs can be landed on a semi-prepared landing area with or without an arrestor system, or into a net. Larger UAVs such as the Global Hawk require a paved runway with the appropriate navigation and landing aids. The requirements for launching and recovering a UAV may therefore have a significant effect on the ground support needed and the equipment required for deployments. [LAX96]

The ideal UAV would be able to be launched from the flight deck of a ship but because of current design restrictions a ship borne UAV airframe capable of attaining the altitudes required and retaining sufficient onboard fuel is not practical. The use of a land based UAV; with a long range deployment capability is currently the best option.

Once airborne the UAV can fly to a pre-determined waypoint or be given enroute course corrections. The ability to be given in flight course corrections is most valuable to the battle group.

I. PAYLOAD

The payload of the UAV is the reason for its existence in the first place. The difficulties with carrying a payload to this portion of the atmosphere are greater than those at lower altitudes. The equipment must be conditioned for the vibration and g-forces of takeoff and landings. The equipment also needs to be conditioned while on orbit.

The primary payload to conduct the intranet mission is a receiver, router, and transmitter. The receiver and transmitter could use LINK 16 with a high security anti-jam capability but with a low data rate. The other option is to use a higher data rate system with a higher probability of jamming or interception. The interception can be handled by assuming the data will always be intercepted and must be guarded by a high

bit-key encryption. The router is the backbone of this system. The router allows the information packets to be sent to their proper destination.

The Globalhawk has the desired space available for this system. There are spaces, conditioned by engine bleed air to 5. PSIA (27,000 ft) and maintained to temperatures between +32 and 131 degrees Fahrenheit. The Global Hawk has sufficient bleed air capacity to more than double the current conditioned volume without impact to the mission performance. [JAG99]

The Global hawk also has the ability to use two 1000 lb pods attached to hardpoints under each wing. These pods could be used for antennas or additional equipment. Because of weight limitations either the EO/IR or SAR antenna and associated payload may have to be removed to maintain the endurance performance.

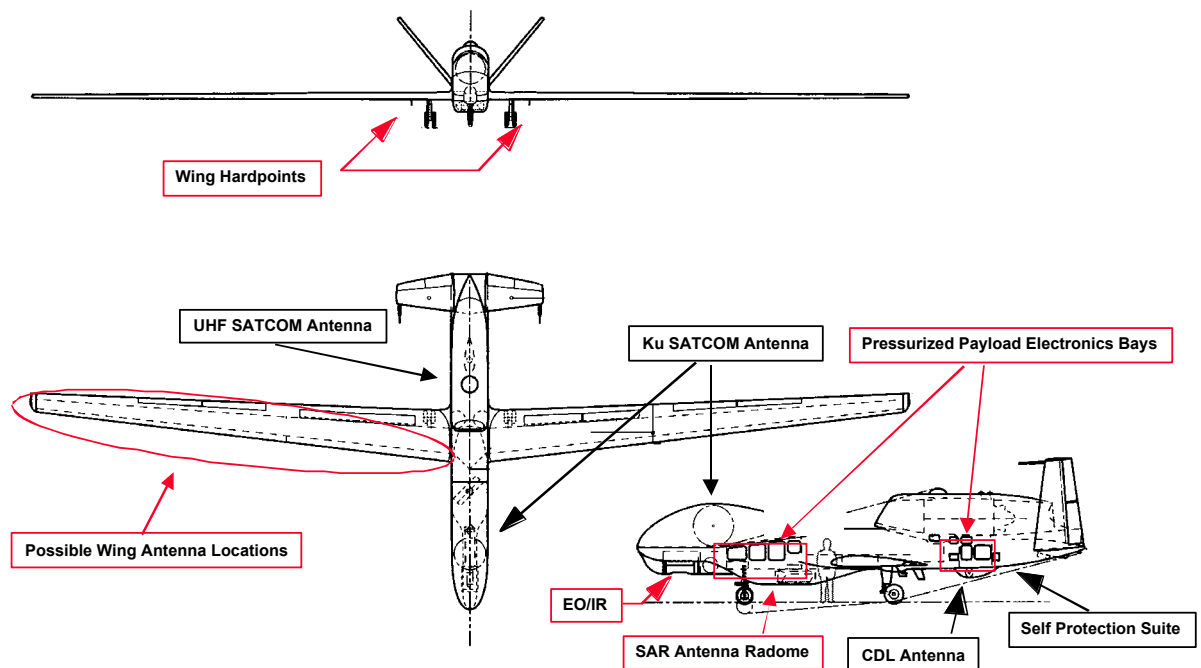


Figure 16 Global Hawk

[From: JAG99]

The forward pressurized compartment is shown highlighted in Figure 17. This compartment has 125 cubic feet of conditioned space. Provisions are made for installation of standard 19-inch rack mounted equipment. A significant fraction of this

volume is used for cableways and provision for airflow and circulation to allow COTS equipment to be employed. Certain avionics in this section (SAR transmitter in the IMINT Global Hawk) have used re-circulated fuel as a cooling medium. The aircraft as a primary heat exchange mechanism uses re-circulated fuel. The EO/IR receiver is located in the nose forward of the pressurized compartment. Removal of this LRU frees up 14 cubic feet and 290 lbs (including ballast). The available space would be readily available for a transmit, receive, router package to be installed. [JAG99]

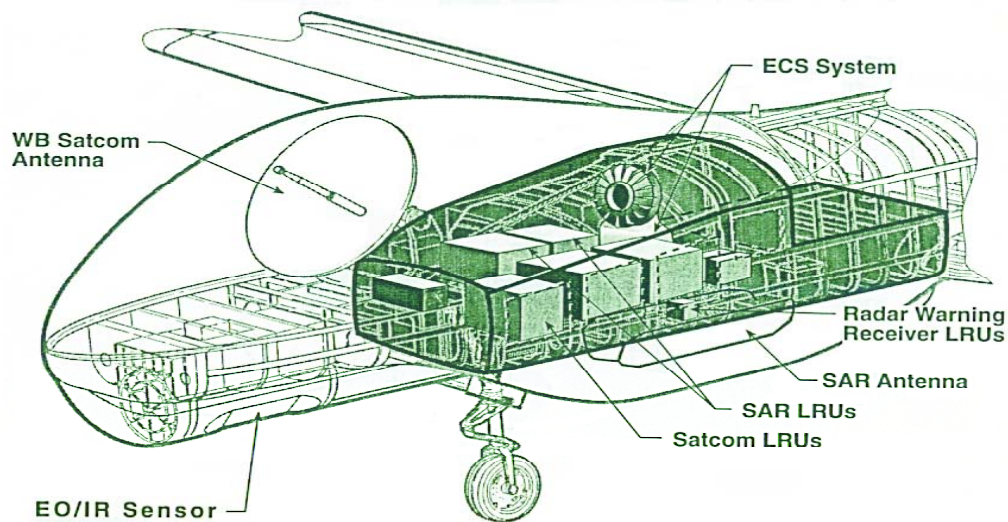


Figure 17 Global hawk Forward Payload Bay

[From: JAG99]

The aft-pressurized compartment, Figure 18, contains electrical distribution, Towed Decoy System electronics, the ALR-89 self-protection system, and Common Data Link LRUs. The compartment is approximately 30 cubic feet in volume, with less than one cubic foot of growth volume for payloads. [JAG99]

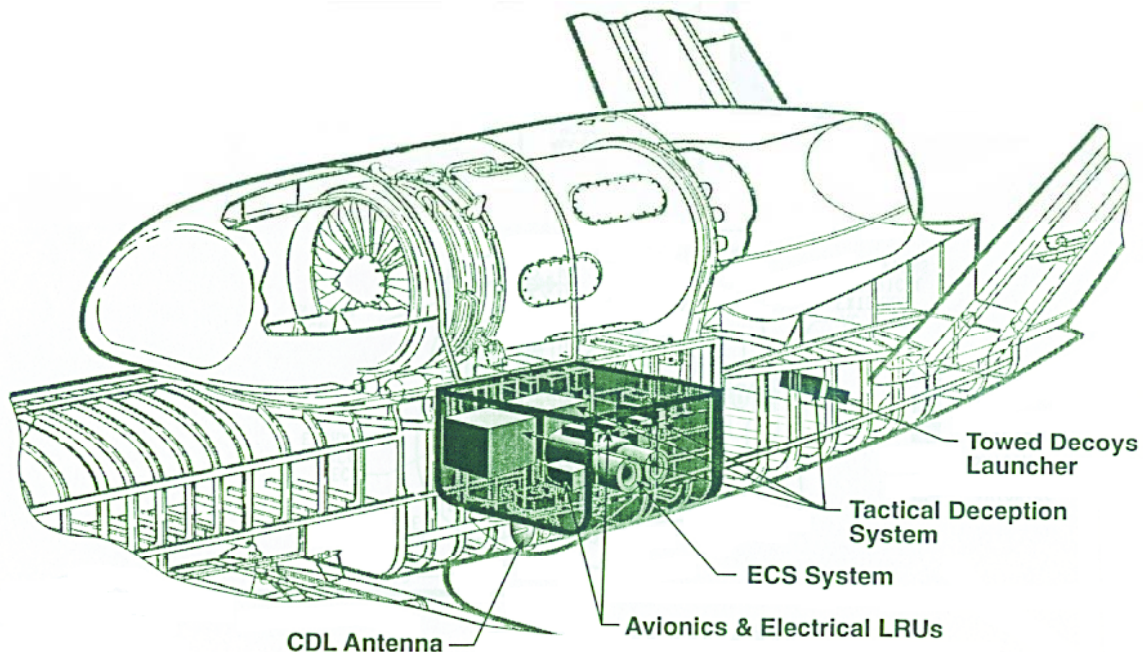


Figure 18 Global hawk Forward Payload Bay

[From: JAG99]

J. POWER

The power available to the UAV is drawn off the engine with no additional APU. The Global Hawk vehicle has one 11.2 kW 28 VDC generator, and one 10 KVA 400 Hz 115/200 VAC generator capable of supplying 8800 watts. One additional pad is available on the engine allowing installation of another alternator adding 8.8 kW capacity. [JAG99]

Table 3 Electrical Power Capacity

	DC Watts	AC Watts	Baseline Total	Add Altenator
Power Available	11200	8800	20000	28800*
Baseline Avionics and Systems	7908	3652	11560	11560
Margin Available	3292	5148	8440	17240*

*Power Extraction Above Baseline Total Results in Reduced Endurance and Altitude

[From: JAG99]

K. ANTENNA DESIGN

The area of antenna design is of great concern because that is one of the largest limiting factors on the bandwidth available. Science Applications International

Corporation (SAIC) has conducted a study investigating the use of Global Hawk as a platform for several different types of communication systems currently in use. The principal of their study was limited to uses by land-based users but the technology has a transparent transfer barrier to naval applications. The SAIC study involved the following services: SINGARS, Cellular, SATCOM, HAVE QUICK, ECT. The sum of the SAIC research gives a starting point for operational testing of antenna placement and design.

L. DEFENSE

Concerns raised about the UAV being a “sitting duck” with no defensive capability abound, however there are several reasons why this is not so. The fact that the UAV would have to operate at an altitude of approximately 65,000 feet provides a defensive barrier with altitude. Currently there only a handful of surface to air missiles designed to attack targets at that altitude. Fighter aircraft have difficulty operating above 50,000 ft and would have limited ability to engage such a UAV. Additionally the UAV would be stationed above a battle group. When activated this air space is some of the most heavily defended area in the world. Because of its location the problem of self-defense is decreased and the greatest threat remains in the electronic spectrum.

M. GLOBAL HAWK

For the purposes of the model in this paper the authors have decided to use the parameter from the Global Hawk UAV as the airborne platform. This was done for several reasons; first it is a system already in the early production phase. As an “off the shelf” airframe many of the design problems have already been solved. Second, the global Hawk system fits the entry-level requirements for an airborne node. Third a preliminary development design has been completed by SAIC, in the design of the antenna systems.

N. WIRELESS COMMUNICATION PLATFORMS

This thesis explores on the use of a UAV as a network node in a battle group intranet. Establishing the basic design parameters for this wireless communication network makes it necessary to define some preliminary considerations before describing the model.

Commercial industry has begun to readily use wireless networks in everyday business practices. Because of this, COTS technology is cheap and relatively easy to implement. The major drawback to using COTS equipment is the lack of confidence in security that it provides. Because current COTS wireless systems are still being evaluated for their encryption capability the authors will use LINK-16 as the wireless connection system in the model. LINK-16 is used because it is a deployed, Jam-resistant, encrypted system. The principles described using LINK-16 as the communication medium can be applied to future wireless communications network projects. Before looking at LINK-16 we will discuss some radio transmission basics.

O. WIRELESS COMMUNICATION BACKGROUND

An electromagnetic signal is a function of time, but it can also be expressed as a function of frequency; that is, the signal consists of components of different frequencies. It turns out that the frequency domain view of a signal is far more important to an understanding of data transmission than a time domain view.

Viewed as a function of time, an electromagnetic signal can be either analog or digital. An analog signal is one in which the signal intensity varies in a smooth fashion over time. In other words, there are no breaks or discontinuities in the signal. A digital signal is one in which the signal intensity maintains a constant level for some period of time and then changes to another constant level.

The spectrum of a signal is the range of frequencies that it contains. The absolute bandwidth of a signal is the width of the spectrum. Many signals have an infinite bandwidth, but with most of the energy contained in a relatively narrow band of frequencies. This band is referred to as the effective bandwidth, or just bandwidth.

There is a direct relationship between the information-carrying capacity of a signal and its bandwidth: the greater the bandwidth, the higher the information-carrying capacity. In general, any digital waveform will have infinite bandwidth. If we attempt to transmit this waveform as a signal over any medium, the transmission system will limit the bandwidth that can be transmitted. Furthermore, for any given medium, the greater the bandwidth transmitted, the greater the cost and typically the greater the size of the antenna. Thus, on the one hand, economic and practical reasons dictate that digital

information be approximated by a signal of limited bandwidth. On the other hand, limiting the bandwidth creates distortions, which makes the task of interpreting the received signal more difficult. The more limited the bandwidth, the greater the distortion and the greater the potential for error by the receiver.[STA02]

P. ANALOG AND DIGITAL DATA TRANSMISSION

The terms analog and digital are used frequently in data communications in at least three contexts: data, signals, and transmission. The principal advantages of digital signaling are that it is generally cheaper than analog signaling and is less susceptible to noise interference. The principal disadvantage is that digital signals suffer more from attenuation than do analog signals.

Digital transmission, is concerned with the content of the signal. A digital signal can be propagated only a limited distance before attenuation endangers the integrity of the data. To achieve greater distances, repeaters are used. A repeater receives the digital signal, recovers the pattern of 1s and 0s, and retransmits a new signal. Thus, the attenuation is overcome. [STA02]

Q. CHANNEL CAPACITY

A variety of impairments can distort or corrupt a signal. A common impairment is noise, which is any unwanted signal that combines with and hence distorts the signal intended for transmission and reception. For digital data, the question that arises is to what extent these impairments limit the data rate that can be achieved. The maximum rate at which data can be transmitted over a given communication path is referred to as channel capacity.

There are four concepts regarding channel capacity.

a. Data rate: this is the rate, in bits per second (bps), at which data can be communicated.

b. Bandwidth: this is the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium, expressed in cycles per second, or Hertz.

c. Noise: this is the average level of noise over the communications path.

d. Error rate: this is the rate at which errors occur, where an error is the reception of a 1 when a 0 was transmitted or the reception of a 0 when a 1 was transmitted.

Communications facilities are expensive and, in general, the greater the bandwidth of a facility, the greater the cost. Furthermore, all transmission channels of any practical interest are of limited bandwidth. The limitations arise from the physical properties of the transmission medium or from deliberate limitations at the transmitter on the bandwidth to prevent interference from other sources. This limitation of bandwidth is further amplified when frequencies cannot be reused because of the power required to reach a satellite can be received over such a large geographic area. This indicates that, all other things being equal, doubling the bandwidth doubles the data rate. Now consider the relationship among data rate, noise, and error rate. The presence of noise can corrupt one or more bits. If the data rate is increased, then the bits become “shorter” so that more bits are affected by a given pattern of noise. Thus, at a given noise level, the higher the data rate, the higher the error rate.

For a given level of noise, it would appear that increasing either signal strength or bandwidth could increase the data rate. However, as the signal strength increases so do the effects of non-linearity in the system, leading to an increase in inter-modulation noise. Note also, that, because noise is assumed to be white, the wider the bandwidth, the more noise is admitted to the system. [STA02]

R. TRANSMISSION MEDIA

In a data transmission system, the transmission medium is the physical path between transmitter and receiver. Transmission media can be classified as guided or unguided. In both cases, communication is in the form of electromagnetic waves. With guided media, the waves are guided along a solid medium, such as copper twisted pair, copper coaxial cable, or optical fiber. These are obviously impractical for communicating between mobile platforms. The atmosphere and outer space are examples of unguided media, which provide a means of transmitting electromagnetic signals but do not guide them; this form of transmission is generally referred to as wireless transmission.

The characteristics and quality of a data transmission are determined both by the characteristics of the medium and the characteristics of the signal. For unguided media, the bandwidth of the signal produced by the transmitting antenna is more important than the medium in determining transmission characteristics.

For unguided media, transmission and reception are achieved by means of an antenna. For transmission, the antenna radiates electromagnetic energy into the medium, air in this case, and for reception, the antenna picks up electromagnetic waves from the surrounding medium. There are two types of configurations for wireless transmission: directional and omni directional. For the directional configuration, the transmitting antenna puts out a focused electromagnetic beam; the transmitting and receiving antennas must therefore be aligned. In the omni directional case, the transmitted signal spreads out in all directions and can be received by many antennas. The system the authors believe would be the best configuration is discussed further in this chapter.

Three general ranges of frequencies are of interest in our discussion of wireless transmission. Frequencies in the range of about 1 GHz (gigahertz = 10^9 Hz) to 40 GHz are referred to as microwave frequencies. At these frequencies, highly directional beams are possible, and microwave is quite suitable for point-to-point transmission. Microwave is also used for satellite communications. Frequencies in the range 30 MHz to 1 GHz are suitable for omni directional applications. We refer to this range as the radio range. [STA02]

S. TERRESTRIAL MICROWAVE

The most common type of microwave antenna is the parabolic “dish”. A typical size is about 3 m in diameter, but they vary greatly in size. The antenna is fixed rigidly, or gimbaled for use on a mobile platform, and focuses a narrow beam to achieve line-of-sight transmission to the receiving antenna. Microwave transmission covers a substantial portion of the electromagnetic spectrum. Common frequencies used for transmission are in the range 2 to 40 GHz, although microwave frequencies are considered to be in the 1 to 40 GHz range. Optimal frequencies are in the 1 to 10 GHz range.

The higher the frequency used, the higher the potential bandwidth and therefore the higher the potential data rate. The table below indicates bandwidth and data rate for typical systems.

Table 4 Data Rates

Band (GHz)	Bandwidth (MHz)	Data Rate (Mbps)
2	7	12
6	30	90
11	40	135
18	220	274

[STA02]

As with any transmission system a main source of loss is attenuation. This is due primarily to range and one reason why UAVs are a good option versus a satellite. Attenuation is increased with rainfall, which could be especially large in a marine environment. The effects of rainfall become especially noticeable above 10 GHz. Another source of impairment is interference. With the growing popularity of microwave, transmission areas overlap and interference with other users is always a concern but less so at sea. The most common bands for long-haul telecommunications are the 4 GHz to 6 GHz bands. With increasing congestion at these frequencies, the 11 GHz band is now coming into use. [STA02]

T. SATELLITE MICROWAVE

A communication satellite is, in effect, a microwave relay station. It is used to link two or more ground-based microwave transmitter/receivers, known as earth stations, or ground stations. The satellite receives transmissions on one frequency band (uplink), amplifies or repeats the signal, and transmits it on another frequency (downlink). A single orbiting satellite will operate on a number of frequency bands, called transponder channels, or simply transponders.

The optimum frequency range for satellite transmission is in the range 1 to 10 GHz. Below 1 GHz, there is significant noise from natural sources, including galactic,

solar, and atmospheric noise, and human-made interference from various electronic devices. Above 10 GHz, the signal is severely attenuated by atmospheric absorption and precipitation.

Most satellites providing point-to-point service today use a frequency in the range 5.925 to 6.425 GHz for transmission from earth to satellite (uplink) and a frequency in the range 3.7 to 4.2 GHz for transmission from satellite to earth (downlink). This combination is referred to as the 4/6 GHz band. Note that the uplink and downlink frequencies differ. For continuous operation without interference, a satellite cannot transmit and receive on the same frequency. Thus the signal transmitted from a ground station must be transmitted back on another. This same design concept would be used with a UAV.

One of the properties of satellite communication should be noted. Because of the long distances involved, there is a propagation delay of about a quarter second from transmission from one earth station to reception by another earth station. This delay is noticeable in ordinary telephone conversations. It also introduces problems in the areas of error control and flow control. This delay would be almost negligible in terrestrial microwave distances using a UAV because of the shorter distances involved. [STA02]

U. MULTIPLEXING

In both local and wide area communications, it is almost always the case that the capacity of the transmission medium exceeds the capacity required for the transmission of a single signal. To make efficient use of the transmission system, it is desirable to carry multiple signals on a single medium. This is referred to as multiplexing.

There are n inputs to a multiplexer. The multiplexer is connected by a single data link to a demultiplexer. The link is able to carry n input signals and transmits over a high capacity data link. The demultiplexer accepts the multiplexed data stream, separates (demultiplexes) the data according to channel, and delivers them to the appropriate output lines.

Two techniques for multiplexing in telecommunications networks are in common use: frequency division multiplexing (FDM), and time division multiplexing (TDM).

FDM takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal. A number of signals can be carried simultaneously if each signal is modulated onto a different carrier frequency and the carrier frequencies are sufficiently separated so that the bandwidths of the signals do not overlap. Each signal requires a certain bandwidth centered on its carrier frequency, referred to as a channel. To prevent interference, the channels are separated by guard bands, which are unused portions of the spectrum.

TDM takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal. Multiple digital signals can be carried on a single transmission path by interleaving portions of each signal in time. The interleaving can be at the bit level or in blocks of bytes or larger quantities. [STA02]

V. COMMUNICATION NETWORKS

1. Types of Networks

Local area networks (LANs), metropolitan area networks (MANs), and wide area networks (WANs) are all examples of communications networks. WANs cover a large geographical area. Typically, a WAN consists of a number of interconnected switching nodes. A transmission from any one device is routed through these internal nodes to the specified destination device.

A LAN is a communication network that interconnects a variety of devices and provides a means for information exchange among those devices. The scope of the LAN is small, typically a single building or a cluster of building. This difference in geographic scope leads to different technical solutions. The internal data rates of LANs are typically much higher than those of WANs. For the purpose of this thesis we will assume the BG is a WAN.

2. Switching Techniques

For transmission of data beyond a local area, communication is typically achieved by transmitting data from source to destination through a network of intermediate switching nodes. The switching nodes are not concerned with the content of the data; rather their purpose is to provide a switching facility that will move the data from node to node until they reach their destination. The end devices that wish to communicate may

be referred to as stations. The stations may be computers, terminals, telephones, or other communicating devices. We will refer to the switching devices whose purpose is to provide communication as nodes. The nodes are connected to each other in some topology by transmission links. Each station attaches to a node, and the collection of nodes is referred to as a communications network. Each ship in the battle group will have a server to act as a node and the UAV will have the central node to link all of the ships together. [STA02]

3. Packet Switching

Data is transmitted in blocks, called packets. A typical upper bound on packet length is 1000 octets (bytes). If a source has a longer message to send, the message is broken up into a series of packets. Each packet consists of a portion of the data (or all of the data for a short message) that a station wants to transmit, plus a packet header that contains control information. The control information, at a minimum, includes the information that the network requires in order to be able to route the packet through the network and deliver it to the intended destination. At each node en route, the packet is received, stored briefly, and passed on to the next node. Because the UAV is the central node it will receive and retransmit packets that are sent to it. Each ship's node will receive all of the packets transmitted from the UAV, via omni directional broadcast, and discard the packets that are not addressed to the ship's server. As an aside note, Omni directional broadcast is used because of the complexity of using multiple gimbaled antennas.

The packet-switching approach has a number of advantages:

- a. Line efficiency is greater, since many packets can dynamically share a single node-to-node link over time. The packets are queued up and transmitted as rapidly as possible over the link.

- b. A packet-switching network can carry out data-rate conversion. Two stations of different data rates can exchange packets, since each connects to its node at its proper data rate.

- c. Unlike a circuit-switching network, calls are not blocked. On a packet-switching network, packets are still accepted, but delivery delay increases. Discarded

packets raises the issue of end-to-end service and reliability. TCP/IP will be discussed in section I, which is a protocol that achieves reliability.

d. Priorities can be used. Thus, if a node has number of packets queued for transmission; it can transmit the higher-priority packets first. These packets will therefore experience less delay than lower-priority packets. This priority system could allow time-critical data, such as radar data, to be given a higher precedence in a combat situation.

Packet switching also has disadvantages relative to other switching techniques:

a. Because the packets between a given source and destination may vary in length, may take different routes, and may be subject to varying delay in the switches they encounter, the overall packet delay can vary substantially. This phenomenon, called jitter, may not be desirable for some applications (for example, real-time applications, including telephone voice and real-time video). This disadvantage would be minimized for intra-battle group traffic because of the minimal distance and hops required when compared to conventional system.

b. To route packets through the network, overhead information, including the address of the destination, and often sequencing information must be added to each packet, which reduces the communication capacity available for carrying user data.

c. More processing is involved in the transfer of information using packet switching than in circuit switching at each node. This is minimized because of the three-node hop in a UAV intranet. [STA02]

W. PROTOCOLS AND TCP/IP

1. Protocol Requirement

There must be a data path between two computers. Typical tasks to be performed include the following:

a. The source system must either activate the direct data communication path or inform the communication network of the identity of the desired destination system.

b. The source system must ascertain that the destination system is prepared to receive data

c. The file transfer application on the source system must ascertain that the file management program on the destination system is prepared to accept and store the file for this particular user.

d. If the file formats used on the two systems are incompatible, one or the other system must perform a format translation function.

The task is broken up into subtasks, each of which is implemented separately. In protocol architecture, the modules are arranged in a vertical stack. Each layer in the stack performs a related subset of the function required to communicate with another system. It relies on the next lower layer to perform more primitive functions and to conceal the details of those functions. It provides services to the next higher layer. Ideally, layers should be defined so that changes one layer does not require changes in other layers. Key features of protocol are: syntax, semantics, and timing. [STA02]

2. TCP/IP Architecture

The TCP/IP protocol architecture is a result of protocol research and development conducted on the experimental packet-switched network, ARPANET, funded by the Defense Advanced Research Projects Agency (DARPA), and is generally referred to as the TCP/IP protocol suite. This protocol suite consists of a large collection of protocols that have been issued as Internet standards by the Internet Architecture Board (IAB).

In general terms, communications can be said to involve three agents: applications, computers and networks. It appears natural to organize the communication task into five relatively independent layers:

a. Physical layer covers the physical interface between a data transmission device and a transmission medium or network. This layer is concerned with specifying the characteristics of the transmission medium, the nature of the signals, the data rate, and related matters.

b. Network access layer is concerned with the exchange of data between an end system and the network to which it is attached. The sending computer must provide the network with the address of the destination computer, so that the network may route the data to the appropriate destination. The sending computer may wish to invoke certain

services, such as priority, that might be provided by the network. The remainder of the communications software, above the network access layer, need not be concerned about the specifics of the network to be used. The same higher-layer software should function properly regardless of the particular network to which the computer is attached.

c. Internet layer is concerned with access to and routing data across a network for two end systems attached to the same network. In those cases where two devices are attached to different networks, procedures are needed to allow data to traverse multiple interconnected networks. Internet Protocol (IP) is used at this layer to provide the routing function across multiple networks. This protocol is implemented not only in the end systems but also in routers. A router is a processor that connects two networks and whose primary function is to relay data from one network to the other on its routed from the source to the destination end system. [STA02]

d. Transport layer, host-to-host exchange of data requires that the data be exchanged reliably. Transport Control Protocol (TCP) is the most common protocol that performs this function.

e. Application layer contains the logic needed to support the various user applications. For each different type of application, such as file transfer, a separate module is needed that is peculiar to that application. [STA02]

3. Internetworking

In most cases, a LAN or WAN is not an isolated entity. Organizations may have multiple LANs of the same type at a given site to accommodate performance or security requirements. And an organization may have LANs at various sites and need them to be interconnected via WANs for central control of distributed information exchange. This is the case for a Navy Battle Group.

a. An interconnected set of networks, from a user's point of view, may appear simply as a large network. However, below are terms that are related to internetworking:

b. Communication network is a facility that provides a data transfer service among devices attached to the network.

c. Internet is a collection of communication networks interconnected by bridges and/or routers.

d. Intranet is an Internet used by a single organization that provides the key Internet applications, especially the World Wide Web. An intranet operates within the organization for internal purposes and can exist as an isolated, self-contained Internet, or may have links to the Internet, our BG example.

e. End system (ES) is a device attached to one of the networks of an Internet that is used to support end-user applications or services.

f. Intermediate system (IS) is a device used to connect two networks and permit communication between end systems attached to different networks. For example, a router on a UAV.

Bridge is an IS used to connect two LANs that use similar LAN protocols. The bridge acts as an address filter, picking up packets from one LAN that are intended for a destination on another LAN and passing those packets on. The bridge does not modify the contents of the packets and does not add anything to the packet. This could be used instead of a router on an UAV; however, it does not forward packets to multiple LANs at once.

Router is an IS used to connect two networks that may or may not be similar. The router employs an Internet protocol present in each router and each end system of the network. The router operates at layer 3 of the OSI model.

Internetworking among dissimilar subnetworks is achieved by using routers to interconnect the subnetworks. Essential functions that the router must perform include the following:

- a. Provide a link between networks
- b. Provide for the routing and delivery of data between processes on end systems attached to different networks

Provide these functions in such a way as not to require modifications of the networking architecture of any of the attached subnetworks. This means that the router

must accommodate a number of differences among networks, such as the following: addressing schemes, maximum packet sizes, interfaces, and reliability. [STA02]

X. ANTENNAS AND PROPAGATION

1. Antennas

In two-way communication, the same antenna often is used for both transmission and reception. Antenna characteristics are essentially the same whether an antenna is sending or receiving electromagnetic energy.

An antenna radiates power in all directions but, typically, does not perform equally well in all directions. An isotropic antenna is a point in space that radiates power in all directions equally. The actual radiation pattern for the isotropic antenna is a sphere with the antenna at the center.. What is important is the relative distance from the antenna position in each direction. The relative distance determines the relative power.

The radiation pattern provides a convenient means of determining the beam width of an antenna, which is a common measure of the directivity of an antenna. When an antenna is used for reception, the radiation pattern becomes a reception pattern. The longest sections of the pattern indicate the best direction for reception.

Antenna gain is a measure of the directionality of an antenna. Antenna gain is defined as the power output, in a particular direction, compared to that produced in any direction by a perfect omni directional antenna (isotropic antenna). Increased power is radiated in one direction by reducing the power radiated in other directions. It is important to note that antenna gain does not refer to obtaining more output power than input power but rather to directionality. Antenna configuration on a UAV will be a key factor as to how well it can send and receive data. When it comes to mobile antennas, frequency and bandwidth go hand and hand. As a general rule, the higher the frequency, the broader the bandwidth will be for a given antenna design. Likewise, the lower the frequency, the more difficult it is to design antennas with sufficient bandwidth.[FIR02]

The system the authors believe would be the best antenna configuration is a gyro-stabilized antenna located on the ships and omni directional antenna on the UAV. This is done to minimize the complexity of placing multiple directional antennas on the UAV

and save weight. Additionally ships have the ability to carry the larger weight associated with a stabilized antenna. [STA02]

2. Propagation

A signal radiated from an antenna travels along one of three routes: ground wave, sky wave, or line of sight (LOS). [STA02] Above 30 MHz, neither ground wave nor sky wave propagation modes operate, and communication must be by line of sight. For satellite communication the ionosphere does not reflect a signal above 30 MHz and therefore a signal can be transmitted between an earth station and a satellite overhead that is not beyond the horizon. For ground-based communication, the transmitting and receiving antennas must be within an effective line of sight of each other. The term effective is used because microwaves are bent or refracted by the atmosphere. [STA02]

3. Line-of-sight Transmission

With any communications system, the signal that is received will differ from the signal that is transmitted, due to various transmission impairments. For analog signals, these impairments introduce various random modifications that degrade the signal quality. For digital data, bit errors are introduced: a binary 1 is interpreted as binary 0 and vice versa. The most significant impairments are attenuation and attenuation distortion. For unguided media, attenuation introduces three concerns:

- a. A received signal must have sufficient strength so that the electronic circuitry in the receiver can detect and interpret the signal.
- b. The signal must maintain a level sufficiently higher than noise to be received without error.
- c. Attenuation is greater at higher frequencies, causing distortion.

The first and second factors are dealt with by attention to signal strength and the use of amplifiers or repeaters. To overcome the [third factor], attenuation distortion, techniques are available for equalizing attenuation across a band of frequencies. One approach is to use amplifiers that amplify high frequencies more than lower frequencies.

In an unguided medium, free space loss is the attenuation as the signal disperses with distance. Therefore, an antenna with a fixed area will receive less signal power the

farther it is from the transmitting antenna. For satellite communication, this is a primary mode of signal loss.

Noise is the major limiting factor in communications system performance. For any data transmission event, the received signal will consist of the transmitted signal, modified by the various distortions imposed by the transmission system, plus additional unwanted signals that are inserted somewhere between transmission and reception.

Noise may be divided into four categories.

a. Thermal noise is due to thermal agitation of electrons. It is present in all electronic devices and transmission media and is a function of temperature. Thermal noise is uniformly distributed across the frequency spectrum and hence is often referred to as white noise. Thermal noise cannot be eliminated and therefore places an upper bound on communications system performance.

b. Intermodulation noise [occurs] when signals at different frequencies share the same transmission medium. Intermodulation noise produces signals at a frequency that is the sum or difference of the two original frequencies or multiples of those frequencies.

c. Crosstalk is an unwanted coupling between signal paths. It can occur by electrical coupling between nearby twisted pairs or rarely, coax cable lines carrying multiple signals. Crosstalk can also occur when microwave antennas pick up unwanted signals; although highly directional antennas are used, microwave energy does spread during propagation. Crosstalk is of the same order of magnitude as, or less than, thermal noise.

d. Impulse noise is non-continuous, consisting of irregular pulses or noise spikes of short duration and of relatively high amplitude. It is generated from a variety of causes, including external electromagnetic disturbances, such as lightning, and faults and flaws in the communications system. Impulse noise is generally only a minor annoyance for analog data, but primary for digital.

An additional loss between the transmitting and receiving antennas is atmospheric absorption. Water vapor and oxygen contribute most to attenuation. Peak attenuation occurs in the vicinity of 22 GHz due to water vapor. At frequencies below 15 GHz, the

attenuation is minimal. The presence of oxygen results in an absorption peak in the vicinity of 60 GHz but contributes less at frequencies below 30 GHz. Rain and fog also cause scattering of radio waves that results in additional attenuation. This can be a major cause of signal loss. Thus, in areas of significant precipitation, either path lengths have to be kept short or lower-frequency bands should be used. [STA02]

4. Fading in the Mobile Environment

Perhaps the most challenging technical problem facing communications systems engineers is fading in a mobile environment. The term fading refers to the time variation of received signal power caused by changes in the transmission medium or path(s). In a fixed environment, fading is affected by changes in atmospheric conditions, such as rainfall. But in a mobile environment, where one or all of the antennas are moving relative to the others, the relative location of various obstacles change over time, creating complex transmission effects.

Three propagation mechanisms comprise multipath propagation.

- a. Reflection occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal.
- b. Diffraction occurs at the edge of an impenetrable body that is large compared to the wavelength of the radio wave.
- c. Scattering occurs if the size of the obstacle is on the order of the wavelength of the signal or less. [STA02]

Y. CODING AND ERROR CONTROL

In previous sections, transmission impairments and the effect of data rate and signal-to-noise ratio on bit error rate were discussed. However, regardless of the design, there will be errors that change one or more bits in a transmitted frame. Three common approaches to coping with data transmission errors follow:

Error detection codes assume that data are transmitted as one or more contiguous sequences of bits, called frames. Probabilities are defined with respect to errors in the transmitted frames. The probability that a frame arrives with no bit errors decreases when the probability of a single bit error increases. Also, the probability that a frame

arrives with no bit errors decreases with increasing frame length; the longer the frame, the more bits it has and the higher the probability that one of these is in error.

Block error correction codes enable the receiver to correct errors in an incoming transmission on the basis of the bits in that transmission. On the transmission end, each k -bit block of data is mapped into an n -bit block ($n > k$) called a codeword, using a forward error correction (FEC) encoder. The codeword is then transmitted; in the case of wireless transmission a modulator produces an analog signal for transmission. During transmission, the signal is subject to noise, which may produce bit errors in the signal. At the receiver, the incoming signal is demodulated to produce a bit string that is similar to the original codeword but may contain errors. This block is passed through an FEC decoder with one of four possible outcomes. The decoder corrects bit errors by adding redundancy to the transmitted message. The redundancy makes it possible for the receiver to deduce what the original message was, even in the face of a certain level of error rate.

Convolutional codes are the other widely used error correcting codes for wireless transmission. If data are transmitted and received in a more or less continuous stream, a block code, particularly one with a large value of n , may not be as convenient as a code that generates redundant bits continuously so that error checking and correcting are carried out continuously. This is the function of convolutional codes. Although similar to block codes, the difference is that convolutional codes have memory. [STA02]

Table 5 Key Data Transmission Terms

Term	Units	Definition
Data element	Bits	A single binary 1 or 0
Data rate	Bits per second (bps)	The rate at which data elements are transmitted.
Signal element	Digital: a voltage pulse of constant amplitude, Analog: a pulse of constant frequency, phase, and amplitude	That part of a signal that occupies the shortest interval of a signaling code
Signaling rate or modulation rate	Signal elements per second (baud)	The rate at which signal elements are transmitted

[STA02]

Z. AIRCRAFT COMMUNICATIONS

1. Communications

An integral piece of the aerial communication system for the BG is the UAV. The Battle Group units use the UAV as a relay station. A transmission from a ship to the aircraft is referred to as uplink, whereas the transmissions from the aircraft to the ship are referred to as the downlink. The electronics in the UAV that takes an uplink signal and converts it to a downlink signal is called a transponder. There are a number of differences between aircraft-based communications and terrestrial wireless communications that affect design:

- a. The area of coverage of an aircraft system far exceeds that of a terrestrial system.
- b. Aircraft power and allocated bandwidth are limited resources that call for careful tradeoffs in ship/aircraft design parameters.
- c. Conditions between communicating aircraft (including satellites) are more time invariant than those between aircraft and a ship or between two terrestrial wireless antennas. Hence, aircraft-to-aircraft communication links must be designed with great precision.
- d. Transmission cost is independent of distance, within the aircraft's area of coverage.
- e. Broadcast, multicast, and point-to-point applications are readily accommodated
- f. Although aircraft links are subject to short-term outages or degradations, the quality of transmission is normally extremely high. [STA02]

2. Capacity Allocation

A single UAV may have a rather large bandwidth and divide it into a number of channels of smaller bandwidth. Within each of these channels, there is a capacity allocation task to be performed. The cost-effective use of the capacity requires that many users share each channel. The task is fundamentally one of multiplexing, which was discussed earlier. All of the allocation strategies fall into one of three categories: Frequency division multiple access (FDMA), time division multiple access (TDMA), and

code division multiple access (CDMA). LINK-16 is an example of a current system, which could be used as a model for future applications. [STA02]

AA. LINK-16

Link-16 provides a robust capability and significant improvement over prior systems: nodelessness, jam resistance, flexibility, increased security, increased number of participants, increased data capacity, navigation features, and voice. Link-16 is as an example of how a transmission system could be designed to create a basic secure BG intranet. The following paragraphs give a brief overview of how LINK-16 works and how a Link-16 like system might be used to solve some of the problems associated with a Battle Group intranet.

JTIDS uses the principle of Time Division Multiple Access to divide network time, and capacity, into divisions called time slots. A unit participating in Link-16, called a JTIDS unit (JU), is assigned either to transmit or to receive in each time slot. There are 128 time slots per second. Time slots are further organized into three sets, each containing 512 time slots, called set A, set B, and set C. To maintain a low probability of exploitation, each set of 512 time slots is not contiguous, but is rather interwoven with those of the other sets. The three interwoven sets of 512 time slots, representing 12 seconds of time, are called a frame. The time slot and the frame are two of the basic units of time in the JTIDS network.

The time slots of each frame are allocated to particular functions. The functional groups used by the Navy are called Network Participation Groups, or NPGs. JUs are assigned to participate in particular NPGs and are allocated a certain amount of those NPGs' capacity for their transmissions. Each JU transmits only during its assigned time slots. The other participants are assigned to receive during these time slots. A JU is either transmitting or receiving, therefore, during any given time slot. The messages exchanged are defined by the J-series message formats. Successful communications require that all terminals of all participants be initialized to transmit and receive at the proper times. [LOG 94]

1. Multi-netting

Network capacity can be further increased by a technique known as multinetting, in which the same time slots are assigned to more than one group of participants and are identified by a net number. The NPG may be the same or different. When the NPG is the same, the structure is referred to as a stacked net. When the NPG is different, the structure is referred to as multiple nets. This increase in capacity is possible because the JTIDS signal is frequency-hopped among 51 different frequencies during each time slot. By varying the sequence, or pattern, in which the frequencies are accessed, it is possible to maintain the separation of these multiple nets. [LOG 94]

2. Relays

The JTIDS signal operates in the UHF band, which limits communication distances to line of sight (LOS). For air-to-air or ship-to-air, the LOS range is approximately 300 nautical miles. For ship-to-ship, however, it is only about 25 nautical miles. Because of this LOS limitation of the JTIDS signal at the earth's surface, relays are necessary for the Battle Group connectivity. To ensure connectivity among all ships, a significant portion of network capacity must be allocated to support the relaying of data.

Specifying the time slot block(s) to be relayed and the amount of delay (6 to 31 time slots) between the original transmission's time slot and the relayed transmission's time slot define relays. Because the entire NPG is relayed, relays double the network capacity allocated to a particular function. [LOG 94]

3. Communications Security

Communications security is provided by four cryptovariables used to encrypt and decrypt data. These cryptovariables are binary keys referred to by numeric labels that are numbers between 0 and 127. Crypto variable labels are assigned to each NPG when the network is designed. The UAV intranet would be more flexible than this allowing change to the network while in operation.

There are two layers of security: message security (MSEC) and transmission security (TSEC). The encryption device to encrypt the tactical data uses the MSEC cryptovariable. The TSEC cryptovariable is a factor in determining the frequency-

hopping pattern, the pseudorandom noise used to mask the signal, and the amount of delay, or jitter, in the start of the data within the time slot. For a unit to receive another unit's transmission, they must both be assigned the same TSEC cryptovariable. For the unit to decrypt the data contained in that transmission, they must both be assigned the same MSEC crypto variable. This type of encryption could be used in a BG WAN to provide greater information security to the network.

For a future intranet instead of just using two layers of message security one concept would be to use a software encryption system, like Pretty Good Protection (PGP), to wrap the data as it is stored on the hard drives of the system. This would make it more difficult for unauthorized personnel to access the information. Even if the MSEC and TSEC were compromised and an unauthorized user gained access to the network they would have difficulty accessing encrypted information on the hard drives. [LOG 94]

4. Data Packing

The JTIDS architecture allows the data to be packed into a time slot in one of four ways: Standard (STD), Packed-2 Single (P2S) Pulse, Packed-2 Double (P2D) Pulse, and Packed-4 Single (P4S) Pulse. These packing structures determine the volume of data transmitted during the time slot. Packed-2 has twice the data that Standard has, and Packed-4 has four times the data. But packing structure affects more than the volume of data carried in each time slot. It also affects the amount of anti-jam margin preserved in the transmitted signal.

In general, the R-S encoded data stream is converted to a series of spread-spectrum transmission symbols that are used to modulate the carrier. Each symbol is transmitted as a pulse. Each pulse is transmitted on a different frequency. The symbol may be transmitted once (single pulse) or twice (double pulse). In the STD and P2D structures, the pulse is transmitted twice. Each transmission is on a different frequency. This redundancy increases the anti-jam margin of the signal. In the P2S and P4 structures, however, the pulse is transmitted only once. This feature could be designed into a new system with the ability of the battle group staff to dial up or down the amount of protection required based on the threat level.

Jitter, a dead time at the beginning of the time slot, also contributes to the anti-jam nature of the JTIDS signal by varying the start of the transmission. There is no jitter when the data is transmitted with the P2D or the P4S structures. The JTIDS terminal determines the packing structure used for a particular transmission automatically. [LOG94]

All of the topics discussed in this chapter are important topics to consider in designing a battle group intranet. While not a comprehensive list these concerns and examples will be addressed where practicable in designing the model portion of this thesis.

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IV. MODELING AND SIMULATION OF NETWORKS

A. INTRODUCTION

Experimentation tests proposals before their implementation thereby avoiding many pitfalls of costly real world experimentation. An example of this is the use of virtual models for the new LPD-17. Sailors are using virtual reality models of works spaces to make design choices for human ergonomics. This use of models is much less costly and more practical than correcting design flaws once the ship is built. Of course there will always be unforeseen events that occur, but experimenting can quash or buttress a proposal because of the insight gained. Resources are the most obvious constraint to testing any proposal. In this case, a US Navy battle group, a Global Hawk UAV, all of the networking components, and many other factors are too costly to *physically* experiment or purchase without first having better understanding of how various systems work together. Simulation and modeling coupled with physically experimenting with the intricacies of interacting systems are necessary to improve war-fighting capabilities.

This thesis proposes an existing model using simulation software from Optimum Network Performance (OPNET) Technologies. The software will be described later in the thesis. Before describing the software that will simulate and model our proposal, modeling and simulation must be addressed first.

B. MODELING & SIMULATION BACKGROUND

Simulation is a procedure in which one system is substituted for another system that it resembles in certain important aspects. It can also be viewed as the act of performing experiments on a model of a given system. By a model, we mean a representation of the system under investigation. [SAD95] Specifically for this project, a USN Battle Group using an UAV as a network link will be modeled.

Simulation emerged as a numerical problem-solving approach during World War II when the Monte Carlo methods were successfully used by John Von Neumann and Stanislaw Ulam of Los Alamos laboratory. The Monte Carlo methods were applied to problems related to the atomic bomb. Simulation was introduced into university

curricula in the 1960s, when books and periodicals on simulation began to appear. The system that is being modeled is deterministic in Monte Carlo simulation, and stochastic in the case of ordinary simulation. [SAD95]

1. The Justification for Simulation

A large number of factors influence the decision to use any particular scientific technique to solve a given problem. The appropriateness of the technique is one consideration; economy is another. [SAD95] Regarding this project, an actual measurement of the effectiveness using a Global Hawk UAV with network equipment and a Battle Group are too costly in manpower as well as other resources. By using simulation, sensitivity analyses can be conducted over time. Further research can be conducted without the trouble of garnering the resources and duplicating circumstances to make minor adjustments for an experiment.

A system can be simplified to such an extent that it can be solved analytically. Such an analytical solution is desirable because it leads to a closed form solution, where the relationship between the variables is explicit. However, such a simplified form of the system is obtained by making several assumptions so as to make the solution mathematically tractable. It is a good first step, but usually not enough. Most real-life systems are so complex that some simplifying assumptions are not justifiable on their own and we must resort to simulation to further investigate and understand system behavior. Simulation imitates the behavior of the system over time and provides data as if the real system were being observed. [SAD95]

Simulation is an appropriate modeling technique in many circumstances. Some useful guidelines and attributes follow:

1. It is the next best thing to observing a real system in operation, if the simulation is of high enough fidelity.
2. It is straightforward and easy to understand and apply. It does not rely heavily on mathematical abstractions that require an expert to understand and apply. [SAD95] Therefore, the system can be widely used by people that aren't considered "experts".

3. Simulation enables the study of, and experimentation with, the internal interactions of a complex system, or of a subsystem within a complex system.
4. Informational, organizational, and environmental changes can be simulated, and the effect of these alterations on the model's behavior can be observed.
5. The knowledge gained in designing a simulation model may be of great value toward suggesting improvement in the system under investigation.
6. By changing simulation inputs and observing the resulting outputs, valuable insight may be obtained into which variables are most important and how variables interact.
7. Simulation can be used as a pedagogical device to reinforce analytic solution methodologies.
8. Simulation can be used to experiment with new designs or policies prior to implementation, so as to prepare for what may happen.
9. By simulating different capabilities for a machine, requirements can be determined.
10. Simulation models designed for training allow learning without the cost and disruption of on-the-job learning.
11. Animation shows a system in simulated operation so that the plan can be visualized.
12. The modern system is so complex that the interactions can be treated only through simulation. [BAN01]

A major disadvantage of simulation is that it may be costly because it requires a large expenditure of time in construction, running, and validation. Another disadvantage is that simulation is difficult to validate and convince others of its utility. Because simulation is a slow and costly technique, it is sometimes referred to as the method of last resort. One should consider using simulation modeling when experimentation with the real system is expensive or dangerous, or when mathematical modeling of the system is intractable. [SAD95] Regarding the previous statements, the advantages of a software

simulation tool with an enormous network model library such as OPNET essentially make the above statement irrelevant regarding cost to construct, slow, etc.

2. Circumstances Where Simulation is Inappropriate

Simulation is of course not a panacea for problem solving. The cost in dollars and time to purchase software, train personnel, and construct models can be substantial. Simulation should be used where it can be considered an enhancement not simply because it can be done. The following guidelines list inappropriate uses of simulation:

1. Simulation should not be used when the problem can be solved using common sense.
2. Simulation should not be used if the problem can be solved analytically.
3. Simulation should not be used if it is easier to perform direct experiments.
4. Simulation should not be used if the costs exceed the savings.
5. Simulation should not be performed if the resources or time are not available.
6. Simulation takes data, sometimes lots of data. If no data is available, not even estimates, simulation is not advised.
7. If there is not enough time or the personnel are not available [to verify and validate the model, simulation is not appropriate.
8. If managers have unreasonable expectations or the power of simulation is overestimated then simulation may not be appropriate.
9. If system behavior is too complex or can't be defined, simulation is not appropriate. [BAN01]

3. Various Simulation Models

A model is a representation of a system. It can be a replica, a prototype, or a smaller scale system. For most analysis, it is not necessary to account for all different aspects of the system. The model simplifies the system to a sufficiently detailed level to permit valid conclusions to be drawn about the system. Depending on the objective being pursued by the analyst, a given system can be represented by several models. A wide variety of simulation models have been developed over the years for system

analysis. To clarify the nature of these models, it is necessary to understand a number of characteristics.

1. Continuous/Discrete Models. This characteristic has to do with the model variables. A continuous model is one in which the state variables change continuously with time. The model is characterized by smooth changes in the system state. A discrete model is one which state variables assume a discrete set of values. The model is characterized by discontinuous changes in the system state. The arrival process of messages in the queue of a LAN is discrete since the state variable, the number of waiting message changes only at the arrival or departure of a message, and changes in discrete, integer steps.

2. Deterministic Stochastic Models. This characteristic deals with the system response. A system is deterministic if its response is completely determined by its initial state and input. It is stochastic (or non-deterministic) if the system response may assume a range of values for given initial state and input. Thus, only the statistical averages of the output measures of a stochastic model are true characteristics of the real system. The simulation of a LAN usually involves random interarrival times and random service times.

3. Time/Event Based-Models. Since simulation is the dynamic portrayal of the states of a system over time, an automatic internal clock must drive a simulation model. In time-based simulation, the simulation clock advances on “tick” of Δt . Although time-based simulation is simple, it is inefficient because some action must take place at each clock “tick”. An event signifies a change in the state of a system. In an event-based simulation model, updating only takes place at the occurrence of event, and the simulation clock is advanced by the amount of time since the last event. Thus, no two events can be processed at any single pass. The need to determine which event is next in event-based simulation makes its programming complex.

4. Hardware/Software Models. Digital modeling may involve either hardware or software simulation. Hardware simulation involves using special-purpose equipment, with detailed programming reduced to a minimum. This equipment is sometimes called a simulator. In software simulation, the operation to the system is modeled using a

computer program. The program describes certain aspects of the system that are of interest. [SAD95]

4. Stages of Model Development

Once it has been decided that software simulation is the appropriate methodology to solve a particular problem, there are certain steps a model builder must take. These steps parallel the six stages involved in model development. In programming terminology, these stages are (1) model building, (2) program synthesis, (3) model verification, (4) model validation, (5) model analysis, and (6) documentation.

1. Model Building: This initial stage usually involves a thorough, detailed study of the system to decompose it into manageable level of detail. The modeler often simplifies components or even omits some if their effects do not warrant inclusion. The task of the modeler is to produce a simplified yet valid abstraction of the system. This involves a careful study of the system of interest. The study should reveal interactions, dependence, and rules governing the components of the system. It should also reveal the estimation of the system variables and parameters. The modeler may use flowcharts to define or identify subsystems and their interactions.

2. Program Synthesis: After a clear understanding of the simplified system and the interaction between components is gained, all the pieces are synthesized into a coherent description, which results in a computer program.

3. Model Verification: This involves a logical proof of the structure of the program as a model. It entails debugging the simulation program and ensuring that the input parameters and logical structure of the model are correctly represented in the code. Although the programmer may know precisely what the program is intended to accomplish, the program may be doing something else.

4. Model Validation: This stage is the most critical. Since models are simplified abstractions, their validity is important. A model is validated by proving it is a correct representation of the real system (verified program can represent an invalid model). This stage ensures that the computer model matches the real system by comparing the two. This is easy when the real system exists.

5. Model Analysis: Once the model has been validated, it can be applied to solve the problem at hand. It involves applying alternative input parameters to the program and observing their effects on the output parameters. The analysis provides estimated measures of the performance of the system.

6. Documentation: The results of the analysis must be clearly and concisely documented for future reference by the modeler or others. [SAD95]

5. Common Mistakes in Simulation

One may ask why mistakes should be listed when a clear set of techniques are also given. However, in the interest of a balanced discussion and to enable the reader to effectively measure the performance of this project, common mistakes in simulation will be discussed.

1. Lack of understanding of the problem: This is perhaps the most common mistake made by inexperienced analysis. It is usual for them to rush into developing a model without a thorough understanding of what they are simulating in the first place. One should try to understand all relevant theoretical background.

2. Ignoring important parameters: The final outcome and validity of a model depend largely on the choices of the parameters describing the system. Ignoring or overlooking important parameters may render the results unacceptable and the model a wasted effort. On the one hand, one must avoid incorporating all parameters relevant to the system, for this may result in a complex model that cannot be solved. A model that is simple and easy to explain is usually preferred to a complex one. On the other hand, one should avoid oversimplification of the system, which will make the results unacceptable.

3. Lack of adequate validation of the model: It has been well said by A. C. Doyle “It is a capital mistake to theorize before you have all the evidence.” It biases the judgment comparing them with those obtained by previous investigators or with similar results obtained using a different approach, which may be analytical or numerical, may validate the results.

4. Poor documentation: A poorly documented program or report does not benefit anyone other than the analyst himself. Both the program and final report on a simulation

model should be properly documented in order to enable users other than the analyst to follow the logic of the model and the program. One common mistake is omitting assumptions and limitations in the documentation. This may cause the analyst or someone else to apply the model in a context where the assumptions are not valid. [SAD95]

6. Common Mistakes in Performance Evaluation

1. No goals. The purpose of simulation is understanding. If there are no expectations for the output of the model how can the success or failure of the model be measured?

2. Biased goals: Another common mistake is implicit or explicit bias in stating the goals.

3. Unsystematic approach: Often analysts adopt an unsystematic approach whereby they select system parameters, factors, metrics, and workloads arbitrarily. The systematic approach to solving a performance problem is to identify a complete set of goals, system parameters, factors, metrics, and workloads.

4. Analysis without understanding the problem: A large share of the analysis effort goes in to defining a problem.

5. Incorrect performance metrics: A metric refers to the criterion used to quantify the performance of the system. A common mistake in selecting metrics is that analysts often choose those that can be easily computed or measured rather than the ones that are relevant.

6. Unrepresentative workload: The workload used to compare two systems should be representative of the actual usage of the systems in the field.

7. Wrong evaluation technique: There are three evaluation techniques: measurement, simulation, and analytical modeling. Analysts often have a preference for one evaluation technique that they use for every performance evaluation problem. There are a number of factors that should be considered in selecting the right technique.

8. Overlooking important parameters: Make a complete list of system and workload characteristics that affect the performance of the system.

9. Ignoring significant factors: Parameters that are varied in the study are called factors. Not all parameters have an equal effect on the performance. Factors that are under the control of the end user (or decision maker) and can be easily changed by the end user should be given preference over those that cannot be changed. For unknown parameters, a sensitivity analysis, which shows the effect of changing those parameters from their assumed values, should be done to quantify the impact of the uncertainty.

10. Inappropriate experimental design.

11. Inappropriate level of detail.

12. No analysis.

13. Erroneous analysis.

14. No sensitivity analysis.

15. Ignoring errors in input.

16. Improper treatment of outliers.

17. Assuming no change in the future.

18. Ignoring variability.

19. Too complex analysis.

20. Improper presentation of results.

21. Ignoring social aspects.

22. Omitting assumptions and limitations.

[JAI91]

7. A Systematic Approach to Performance Evaluation

1. State goals and define the system.

2. List services and outcomes.

3. Select metrics.

4. List parameters.

5. List factors to study.

6. Select evaluation technique.
7. Select workload.
8. Design experiments.
9. Analyze and interpret data.
10. Present results.

[JAI91]

8. Selection of Techniques and Metrics

Selecting an evaluation technique and selecting a metric are two key steps in all performance evaluation projects. The key consideration in deciding the evaluation technique is the current life-cycle stage of the system. Measurements are possible only if something similar to the proposed system already exists, as when designing an improved version of a product. If it is a new concept, analytical modeling and simulation are the only techniques from which to choose. Analytical modeling and simulation can be used for situations where measurement is not possible, but in general it would be more convincing to others if the analytical modeling or simulation is based on previous measurement. [JAI91]

The next consideration is the time available for evaluation. [JAI91] According to the reference material, analytical modeling is the only quick way to get results, with measurements and simulation following in that order. However, the scope of this project is to determine the feasibility of a wireless network that uses an UAV. Measurements are beyond the funding resources of this project and analytical techniques would not provide a demonstrable level of achievement.

The level of accuracy desired is another important consideration. In general, analytical modeling requires so many simplifications and assumptions that if the results turn out to be accurate, even the analysts are surprised. Simulations can incorporate more details and require [fewer] assumptions than analytical modeling and, thus, more often are closer to reality. [JAI91] This is a key point. Once a viable model is developed for a simulation, it can be tuned to reflect a more accurate picture of an actual system.

9. Advantages and Disadvantages of Simulation

Simulation is very attractive because it mimics the events in the real world. The output data from a simulation should directly correspond to the outputs that could be recorded from the real system. The advantages of simulation are:

a. New policies, operating procedures, decision rules, information flows, organizational procedures, and so on can be explored without disrupting ongoing operations of the real system.

b. New hardware designs, physical layouts, transportation systems, and so on, can be tested without committing resources for their acquisition.

c. Hypotheses about how or why certain phenomena occur can be tested for feasibility

d. Time can be compressed or expanded allowing for a speedup or slowdown of the phenomena under investigation.

e. Insight can be obtained about the interaction of variables.

f. Insight can be obtained about the importance of variables to the performance of the system.

g. Bottleneck analysis can be performed indicating where work-in-process, information, materials, and so on are being excessively delayed.

h. A simulation study can help in understanding how the system operates rather than how individuals think the system operates.

i. “What-if” questions can be answered. This is particularly useful in the design of new systems.

The disadvantages are:

a. Model building requires special training. It is an art that is learned over time and through experience. Furthermore, if two competent individuals construct two models, they may have similarities, but it is highly unlikely that they will be the same.

b. Simulation results may be difficult to interpret. Since most simulation outputs are essentially random variables (they are usually based on random inputs), it may be hard to determine whether an observation is a result of system interrelationships or randomness. Making minor changes to single numerical parameters, and statistical distribution may minimize this. Additional major changes to logical model subsystem structure or a new model design can solve this problem.

c. Simulation modeling and analysis can be time consuming and expensive. Skimping on resources for modeling and analysis may result in a simulation model or analysis that is not sufficient for the task.

d. Simulation is used in some cases when an analytical solution is possible, or even preferable. This might be particularly true in the simulation of some waiting lines where closed-form queuing models are available.

In defense of simulation, these four disadvantages, respectively, can be offset as follows:

Vendors of simulation software have been actively developing packages that contain all or part models that need only input data for their operation. Such models have the generic tag “simulators” or “templates”.

Many simulation software vendors have developed output analysis capabilities within their packages for performing very thorough analysis.

Simulation can be performed faster today than yesterday, and should be even faster tomorrow. This is attributable to the advances in hardware that permit rapid running of scenarios. It is also attributable to the advances in many simulation packages.

Closed-form models are not able to analyze most of the complex systems that are encountered in practice.[BAN01]

10. Selection of Simulation Software

There are many simulation software packages available today and there are many relevant features to choose from before selecting the software for any given project. Below are some guidelines to follow in order to evaluate and eventually select particular software:

Do not focus on a single issue such as ease of use. Consider the accuracy and level of detail obtainable, ease of learning, vendor support, and applicability to your problems.

Execution speed is important. Speed of the simulation affects development time. During debugging, an analyst may have to wait for the model to run up to the point in simulated time where an error occurs many times before the error is identified

Beware of advertising claims and demonstrations. Many advertisements exploit positive features of the software only. Similarly, the demonstrations solve the test problem very well, but perhaps not your problem.

Ask the vendor to solve a small version of your problem.

Beware of “checklists” with “yes” and “no” as the entries. However, implementations have considerable variation and level of fidelity. Implementation and capability are what is important.

Simulation users ask if the simulation model can link to and use code or routines written in external languages such as C, C++, or FORTRAN. This is a good feature, especially when the external routines already exist and are suitable for the purpose at hand. However, the more important question is whether the simulation package and language are sufficiently powerful to avoid having to write in any external language.

There may be a significant trade-off between the graphical model-building environments and ones based on a simulation language. While graphical model building removes the learning curve due to language syntax, it does not remove the need for procedural logic in most real-world models and the debugging to get it right. Beware of “no programming required” unless either the package is a near-perfect fit to your problem domain, or programming (customized procedural logic) is possible with the supplied blocks, nodes, or process flow diagram, in which case “no programming required” refers to syntax only and not the development of procedural logic. [BAN01]

C. OPNET

A modeling and simulation tool has been selected for this project as mentioned earlier OPNET Technologies' MODELER (including the requisite Radio Module because the network is wireless). Background on this simulation software tool follows.

1. Capabilities

The OPNET simulation software has the ability to build Hierarchical network models: manage complex network topologies with unlimited sub-network nesting. It can model wireless, point-to-point, and multipoint links. This is the portion of the software that makes it a good tool for modeling a fleet and UAV interaction. The mobile marine environment creates different problems than those normally associated with land based wireless networking.

OPNET can incorporate physical layer characteristics, environmental effects, account for delay, availability, and throughput characteristics of links. OPNET's ability to use geographical and mobility modeling by controlling each node's position dynamically or predefine trajectories. Maps and other background graphics can be added to facilitate graphical representation for easier assimilation of data.

Results from OPNET are easily interpreted with comprehensive tools to display, plot and analyze time series, histograms, probability functions, parametric curves, and confidence intervals, which can be exported to spreadsheet form.

2. Various Models

The main advantage in selecting this software is the vast library of models that are readily available and accepted within the industry.

Data Link Layer

Asynchronous Transfer Mode (ATM)

Ethernet

Fiber Distributed Data Interface (FDDI)

Frame Relay

LAN Emulation (LANE)

Link Access Procedure, Balanced (LAPB)

Sliding Window Protocol (SWP)

Spanning Tree Bridge (STB)

Spatial Reuse Protocol (SRP)

Token Ring

X.25

Routing Protocols

Border Gateway Protocol (BGP)

Interior Gateway Routing Protocol (IGRP)

Open Shortest Path First (OSPF)

Routing Information Protocol (RIP)

Transmission Protocol

Transmission Control Protocol (TCP)

Transport Adaptation Layer

Network Layer Protocol

Internet Protocol (IP)

Resource Reservation Protocol (RSVP)

IPX

Miscellaneous Models

Applications Model

ISDN/xDSL

Job Service Discipline (JSD)

Raw Packet Generator (RPG)

Static Distributed Routing (SDR)

Vendor Models

Wireless LAN (802.11)

Specialized Models

Circuit-Switched

DOCSIS

IP Multicasting

Multi-Protocol Label Switching (MPLS)

Private Network-Network Interface (PNNI)

[OPN00]

3. Radio Module

The Radio Module provides the added capability of modeling radio links and mobile communications nodes. Mobile nodes include ground, airborne and satellite systems. Mobile node models incorporate three-dimensional position attributes that can change dynamically as a simulation progresses. Node motion can either be scripted as a position history or determined on an adaptive basis by position control processes. Node movement can be automatically displayed during or after a simulation with OPNET 's animation features. Network diagrams and animations can include standard or custom map backdrops.

D. MODEL IMPLEMENTATION

The recommendation for implementation of the model will now be discussed. This chapter will evaluate a model that possesses characteristics necessary to test the scenario proposed in this thesis. The model is a baseline scenario obtained from www.opnet.com. A search was conducted for contributed models that resembled the research that we are conducting that could be modified to fit our proposal. The search was limited to models that could run OPNET 7.0 or later. There are many models with previous software versions available on the website. Converting the legacy model files proved to be quite difficult because documentation is often not available. OPNET does not maintain or update any of the contributed models and many of them have widely varying goals. Additionally, the authors of models are not always identified.

Once on OPNET's website, use the scroll-down menu and look up Contributed Model Depot. After the page appears, click Search in the upper right corner. By clicking Search, the page for conducting queries will appear noting; that there are 166 models to choose from at the time this thesis is published. One can query by key word or search the entire list of models page by page. As noted above, OPNET does not validate nor update the Contributed Model Depot web page.

The architecture of the model we chose is related to the employment of a UAV communication node in a BG. The only documentation is the author's description of the project. An individual's own understanding of the subject and OPNET are required in order to investigate the performance and parameters input into the model. Before

describing the model we have chosen, we will note here the other related models that may be useful for future research or as models that can be incorporated into the UAV/BG scenario model that we will describe. The title, author, and description are listed below:

Generic Satellite Palette by John Strohm: A series of devices meant to emulate a generic geosynchronous satellite network. Ground stations connect to a satellite with duplex links which model the transmission delay.

Aircraft Internet Access Study by anonymous author: Study the effects of deploying internet access from an aircraft. Low Earth Orbit Satellite Study by Farzam Toudeh-Fallah: This study compares buffering and non-buffering in a low earth orbit satellite scenario.

Geocast by Francesco DelliPriscoli: Geocast project deals with a satellite system composed by a geo-stationary satellite, several spot-beams and a network control center (NCC). The traffic terminals (TTs) in the spots pick up the traffic generated by the sources and forward bandwidth request to the NCC. The NCC shares bandwidth among requesting TTs using a DAMA (Demand Assignment Multiple Access) protocol. The whole system aims to reach the best bandwidth utilization and the minimum end-to-end delay.

Satellite communication using routing set and minimum flow by Roy Kucukates: This project simulates the satellite network based on Finite State Automation (FSA) and tries to minimize the maximum flow (MFMR) over the routing set (RS) concept. There are various scenarios for different loads and source-destination pairs in the model. The main performance issue is the maximum flow over the existing links, second is the average delay and then the maximum buffer requirements of the satellite nodes. The mobility of the terminals and the satellites are not considered in the model since it is based on FSA assumption.

VSAT by Russell Elsner: Small network with 2 LEO satellites that provide data connection between South America and Africa. This model studies the effect of adding buffers to the satellites. The statistics of interest are Throughput and End-to-End delay.

Wireless ATM by Bill Cooper: Integrates the ATM Forum's Wireless ATM specification into the standard OPNET ATM models. Used to simulate Wireless ATM performance in a LEO Satellite Network.

E. LEO SATELLITE NETWORK MODEL

Brian Chau's LEO Satellite Network Model was chosen for practical reasons as well as potential to contribute to further research for the subject of this thesis. The practical reason is the relatively recent version of OPNET Modeler 7.0. Also, as we've shown in previous chapters, a UAV provides many of the advantages that a LEO satellite possesses in addition to advantages that a terrestrial link has.

F. DOWNLOADING MODEL

Once at the contributed models page of OPNET, type in "leo satellite network" to query the database. Click download to begin the process of saving the zip file.

Open OPNET and click Preferences under Edit. Scroll down to mod_dirs and click the box titled Value. Specify the path to the directory where the model is saved then select OK twice. Click File then Refresh Directories before going on to click File again. After selecting File again, click Open. The default setting in the menu scroll is Project, but if it does not appear scroll down and select it before going any further. Search for the model title, leo_sat_network. Highlight the title then click OK. The network topology for the model will not appear until the user clicks Scenarios at the top of the toolbar then Switch To. Sixteen various options were available for the authors to view and run. However, the topology for each one is the same as below in Figure19.

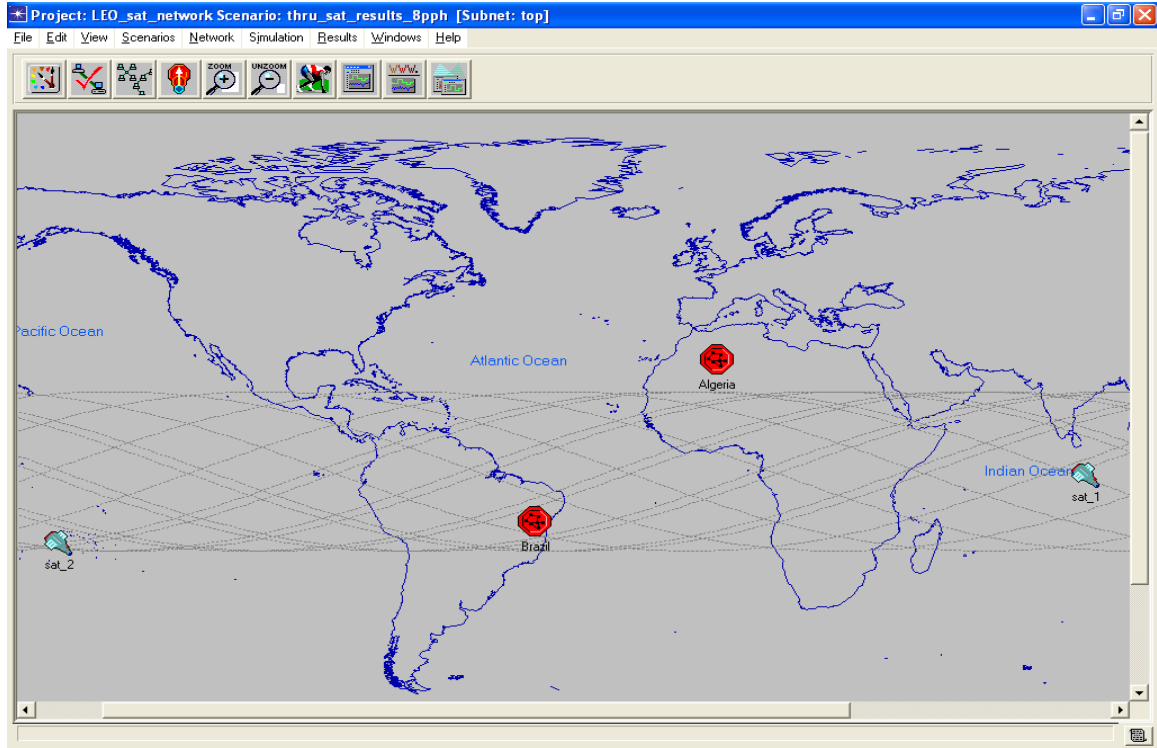


Figure 19 Network Topology

G. MODEL DESCRIPTION

From the README file, the author, Brian Chau, describes the model as follows:

“This project contains a simple radio network. It contains two sub-networks, one in Brazil and the other in Algeria. Mobile users from each sub-network generate traffic that is destined for broadcast in the other sub-network. This project studies the effect of using two LEO (low earth orbit) satellites with and without on-board data buffers.

There are many different scenarios that measure the throughput and end-to-end delay through the network; each with different traffic loads. There are also scenarios that have animations associated. The animations contain custom animation code. There are also two scenarios that produce scalar data, one for the buffered and one for the unbuffered satellite.

The mobile users send data packets to the local base station using a CSMA protocol. This data is then queued at the base station until it can be uploaded to the satellite. In the unbuffered satellite case, the base station must wait to hear the control

signal from the other base station before sending a packet. This ensures that the satellite has line-of-sight to both base stations.

In the buffered satellite case, the base station waits until it hears its own control signal returned from the satellite. This ensures that the satellite has line-of-sight to the base station. For every control signal that is returned, a data packet can be sent to the satellite. It will be queued on the satellite until line of sight is established with the destination base station.”

In Figure 20 are the attributes for Satellite 2 and the Brazil subnet. The attributes for the two satellites are identical and the two-subnet nodes – Brazil and Algeria, are also identical.

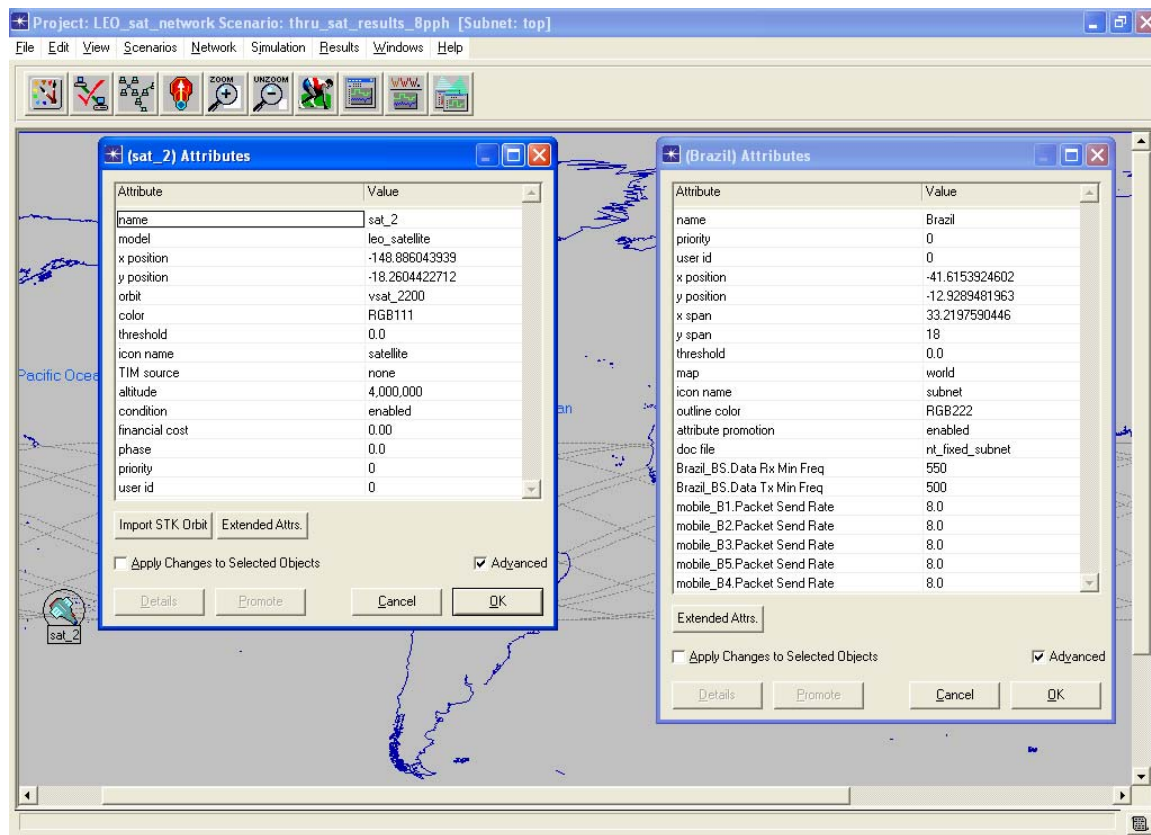


Figure 20 Satellite 2 and the Brazil Subnet

Figure 21 is the Brazil subnet node architecture. Since OPNET uses a hierarchical set of graphical editors, a user can progressively develop more detailed attributes for the nodes by clicking on each one of the nodes. One can view the Brazil

subnet by double clicking. The zigzag lines in Figure 3 are the trajectory paths that were defined by a series of 11 Cartesian coordinates. By right clicking on the mouse, the trajectory can edit this attribute.

In order to adapt this topology to our proposed BG scenario, an additional 4 nodes would be added to this architecture for a total of 10 nodes. Also, the base station would be mobile in order to represent the carrier while the other mobile nodes would represent the various ships throughout the BG. The trajectory paths would also need modification. Overall, the speed of the mobile nodes would be slower and the trajectory paths would be more uniform for the BG. Under those conditions, one could expect a more favorable outcome in bit error rate.

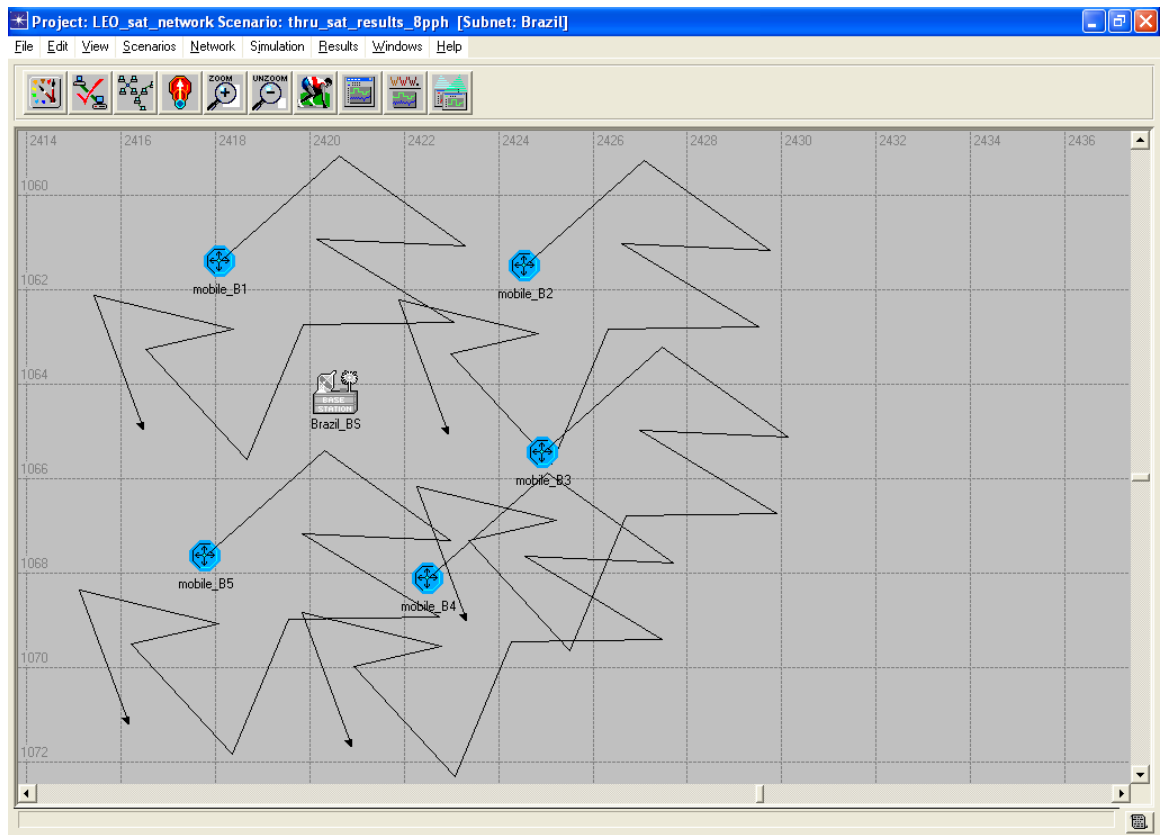


Figure 21 Brazil Subnet Node Architecture

The mobile node attributes and base station attributes are shown in Figure 22 below. For the base station, the minimum receiving frequency is 350 MHz, minimum transmitting frequency is 300 MHz, and the altitude is set at 300. Altitude does not have units associated with it, so the figure is a default value in meters. The node is a

leo_sat_basestation model in OPNET. A user can modify this by clicking on the description and then edit. Mobile node attributes within the subnets are set at 50 for altitude and a ground speed of 2 meters per second. Again, the altitude is a relative value. The node is a leo_sat_mobile model, which can be modified in the same fashion as the base station node.

Although not shown, the attributes editor for the satellites depicts an altitude of 4,000,000 meters and the orbit model is vsat_2200. There is an option for no model as well as low_earth, low_earth24, and rec_sat. OPNET has a built in pathway to import Satellite Tool Kit (STK) by Analytical Graphics, Inc. if the models provided are not sufficient. Satellite Tool Kit is a widely accepted satellite simulation software tool. In our proposed scenario, OPNET by itself is incapable of modeling a UAV flying over a Battle Group in a racetrack pattern.

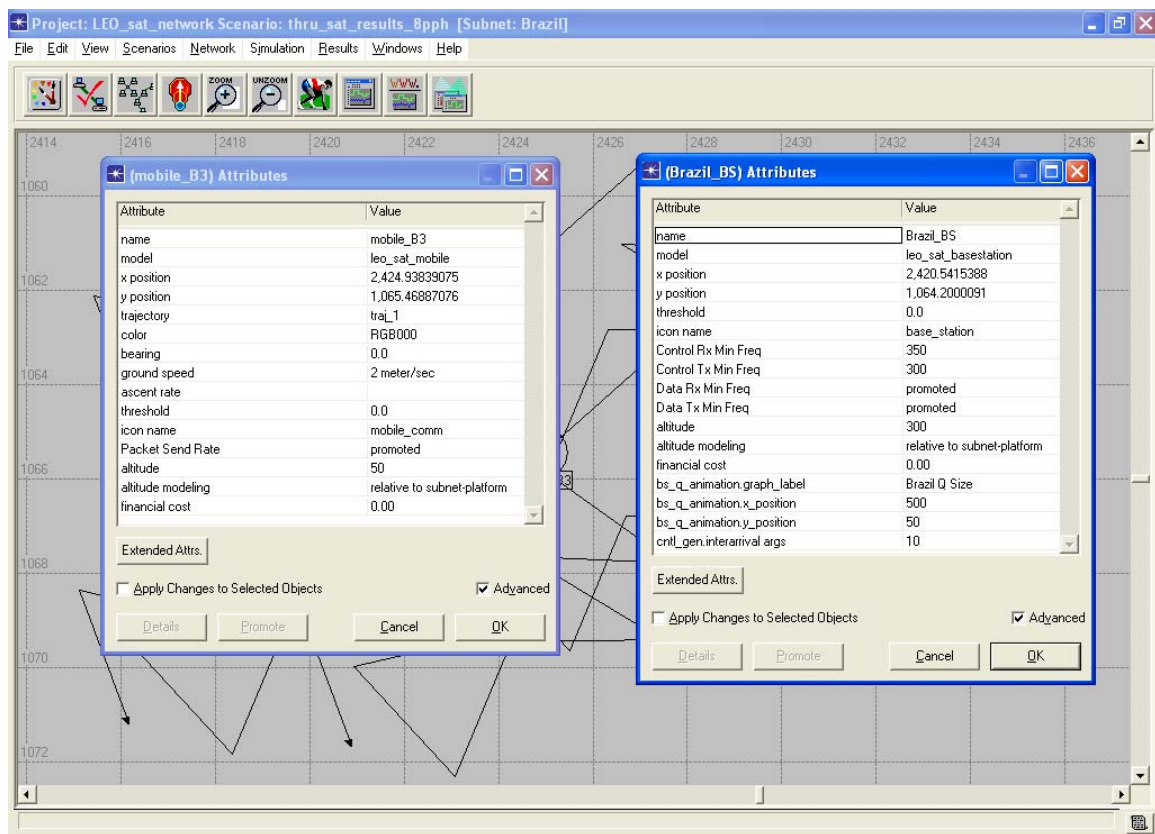


Figure 22 Mobile Node Attributes

The mobile nodes are all identical and the architecture can be seen through the node editor in Figure 23 below. Data flow and the physical resources are depicted in the

editor. Network devices and the system can be edited by a right click of the mouse. The antenna model is isotropic, which has a uniform gain in all directions. The pointing reference theta is 180 degrees. The other option is directional, so the user must define the pattern.

By double clicking `m_queue`, `m_generator`, `local_sink`, and `remote_sink`, the process editor can be opened in order to graphically specify the level of detail for these processes in response to events. The process editor in OPNET uses a finite state machine approach to enable the user to specify the details. Default settings are provided with the model; however, they can be modified. Packet generators use an exponential distribution instead of constant; however this could be modified via the edit mode.

Transmitter modules transmit packets to the antenna at 1024 bits/second, using 100 percent of its channel bandwidth. For each arriving candidate packet, the receiver module consults several properties to determine if the packet's average BER is less than some specified threshold. If the BER is low enough, the packet is sent to the sink and destroyed. [OPN01]

The processor module calculates the latitude, longitude, and altitude coordinates the antenna requires to aim at a specific target. The pointing processor makes this calculation by using a kernel procedure that converts a node positions in a subnet (described by the x position and y position attributes) into the global coordinates the antenna requires. [OPN01]

OPNET also provides a jammer node that introduces noise into the network. This should be introduced in later research in order to provide a more accurate depiction of a real world scenario.

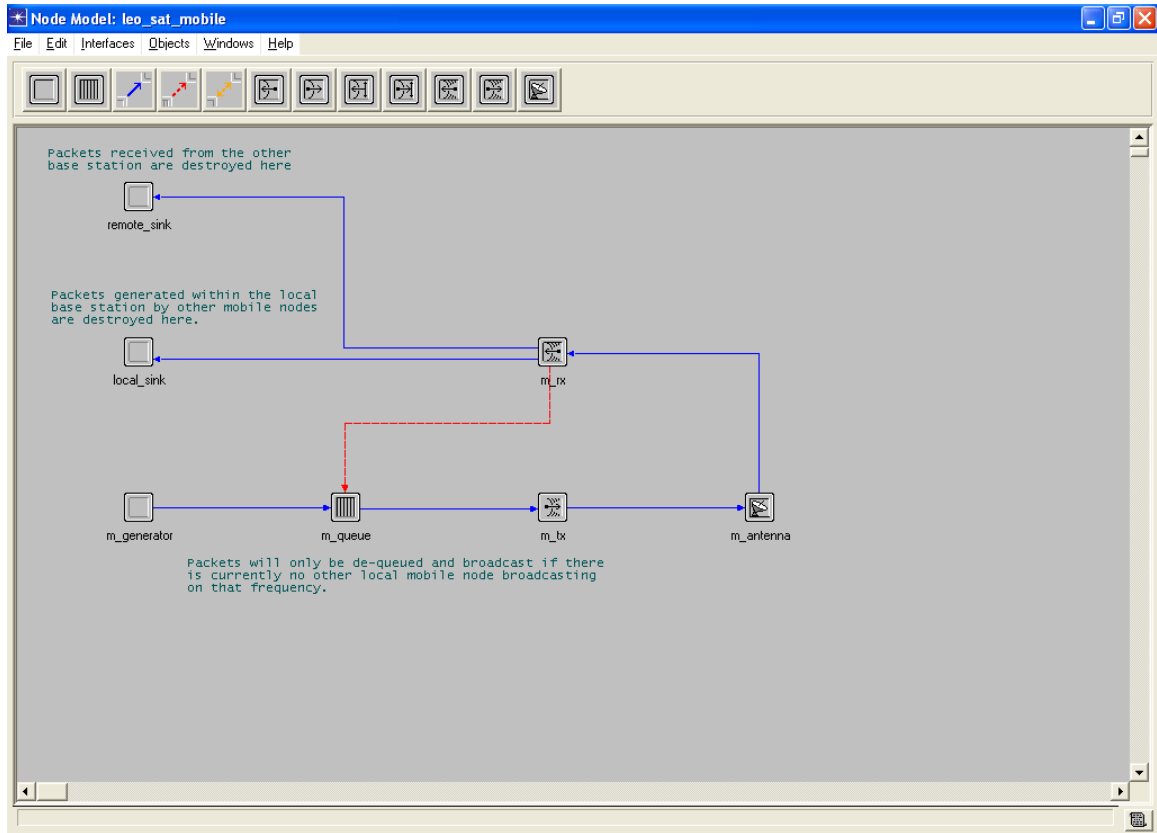


Figure 23 Mobile Nodes Architecture

In Figure 24 below, on the left hand side, a user can select the statistics to view for further analysis and the results of the analysis are shown on the right. The quantity and detail of reports are scalable in OPNET. In this example, nearly all of the options are selected for thru_8_pph scenario. The statistics gathered are delay, queue size, throughput, and load. Global statistics as well as individual subnet statistics are computed.

A user can change the collection mode for different statistics. These modes specify the way in which statistics are captured (all values, bucket, sample, glitch removal), as well as their collection mode. [OPN01] Additionally, the sample frequency can be manually set for each collection mode selected.

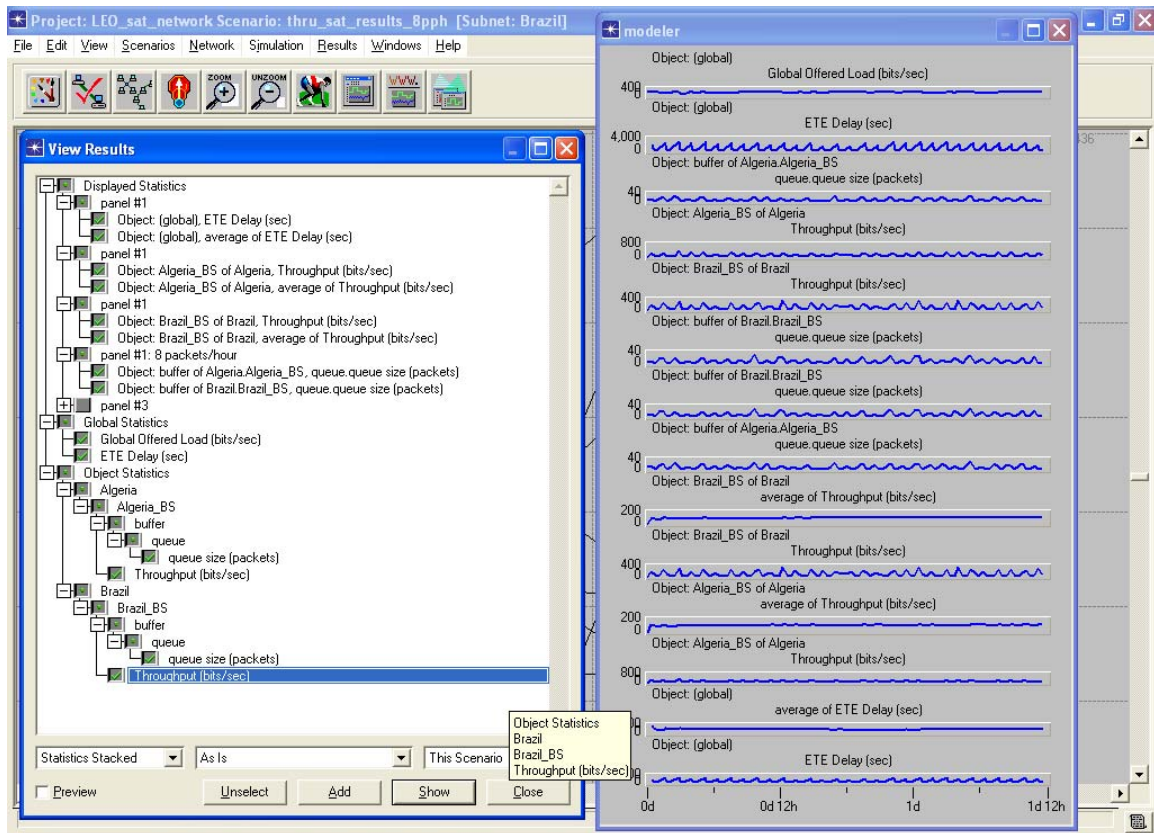


Figure 24 Statistics

Finally, Figure 25 demonstrates the animation viewer whereby events for a particular scenario are visually displayed. The buffers for each satellite flash on the screen in the upper left hand corner bar charts once the animation begins to run. The relative size of the queue is shown in red. Blue and green lines flash for varying lengths of time to indicate transmission of packets. The satellites change their position periodically and only one satellite at a time is actually shown communicating with the ground base stations. Toolbar options at the top of the window allow the user to control the animated simulation.

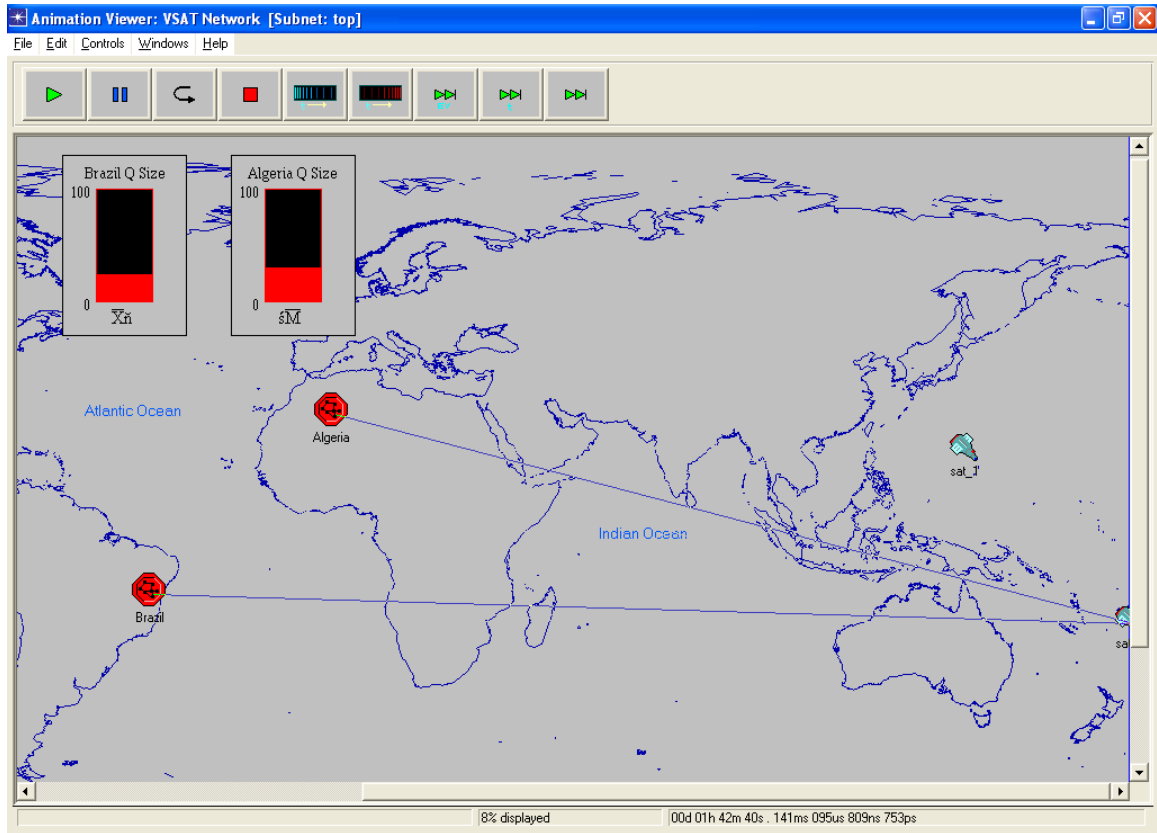


Figure 25 Demonstration of Animation

H. TRANSFORMING MODEL FROM LEO TO UAV/BG

Before developing a model for a battle group using an UAV as a communication node in the network, requirements must be well established. IT 21 a current measuring tool for future communication trends. Future requirements are expected to put increasing pressure on existing systems regarding multimedia, communications, and other services. That expected growth could be handled by UAVs, so a model that is flexible, but provides the planner with a best-effort goal is what we are proposing.

Network latency results from queuing, switching, and link-layer medium access control (MAC) bandwidth allocation as well as from serialization and propagation delays. With the exception of the total path propagation delay, where the speed of light is a common constraint, these contributing delays will vary considerably according to the specific system design. As a first approximation, these delays can be thought of as proportional to the number of wireless links traversed. [LLO01]

Examining the shortest-path propagation delay across a network provides a best-effort goal with which real-world performance could be compared. [LLO01] Link analysis (power, antenna gain, path, attenuation factors, noise, BER) is the first step in establishing the parameters for current and projected (required) throughput. The link budget is crucial because analysis of current systems provides a good measure of accuracy when comparing to future simulated results. Therefore, 2 link budgets should be derived for current and future systems.

The model we have selected is desirable because it can be modified to accommodate our proposed scenario of a UAV flying in a racetrack pattern over a BG, but also internetworking with other land, naval, and satellite networks. As mentioned above the link budget must be derived as the first step. Next the trajectories of the mobile nodes must reflect simple ship courses in a BG. STK must then be used to create a flight pattern that has a footprint over the BG. Once STK has been imported, the model will be ready to run. Of course only one of the satellite nodes will be used in our proposed scenario, but the next step is to establish a link between the satellite (UAV) nodes.

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V. CONCLUSIONS

In this final chapter a summary is provided to encompass all of the topics covered in this thesis. Secondly the authors will provide their general conclusions with regard to the application of a UAV in a battle group intranet and the ability to show a basic model. Finally recommendations are made for further research to be accomplished in this area. This thesis began with a short overview of UAVs and how the GLOBAL HAWK UAV could be used as a node to connect a battle group WAN. Also, a concept of operations for the use and implementation of UAVs in a battle group wireless intranet was discussed.

A. SUMMARY

A concept of operations covering a small spectrum of uses for a UAV as the central node in a battle group intranet was discussed. Furthermore, a discussion on network design and some of the factors affecting how a UAV might be implemented were discussed. Finally, two chapters provided details regarding model design and the authors' description of a proposed model from OPNET's website for contributed models.

B. CONCLUSIONS

There are a number of conclusions that the authors arrived at during the course of research. The following are those considered most pertinent. The research conducted provided support for the UAV concept as a viable option and it should be further studied.

The most viable conclusions that can be drawn from this research:

- a. COTS equipment is a viable option for installation on the UAV.
- b. Current UAV designs prohibit it from being an organic Battle group asset, but an argument can be made as a theater deployable asset to support a battle group.
- c. If the UAV concept is used it will free up valuable satellite time allowing currently constrained systems to operate more efficiently. The UAV is not a replacement for satellite communications but a complement to its capabilities.
- d. The ability to service UAV's to upgrade the onboard equipment makes them adaptable and not a legacy system to retard future war fighting concepts.

e. The model chosen can be adapted to test the feasibility of the proposed scenario with very little modification.

f. The model that was chosen demonstrated a worst-case scenario in feasibility because of limited overhead time, small footprint, and propagation delay.

g. The model uses two LEO satellites which demonstrate the possibility of using two UAV's to connect a carrier battle group and an amphibious ready group simultaneously while separated by an even larger distance.

h. Scalable networks using UAVs in a tactical environment can be simulated in OPNET.

Difficulties discovered with this model:

a. Simulating a UAV orbit in OPNET requires trajectories and is therefore unrealistic and too difficult. Hence, an additional simulation tool such as STK must be used.

b. Although OPNET is a powerful and effective modeling and simulation tool, incorporating various attributes from a link budget such as altitude, transmitter power, and bandwidth can require significant time in order to gain the familiarity to run the system.

c. Due to the complexity of the model, we were unable to test the feasibility of the network communication plan, and how attenuation factors, i.e. rain, dust, and noise would affect the performance of the model.

d. Difficulties encountered with the model can be overcome. Further analysis is required in order to determine precisely what modifications to this model are necessary in order support the UAV battle group intranet concept.

C. RECOMMENDATIONS

The research conducted in this thesis suggests that the use of a UAV as an internal node in a Battle Group intranet is a feasible option. The technology required to outfit a Global Hawk UAV and place it in operation is available today. Further research using the modeling and simulation tool OPNET for this concept is justified. Significant savings in money and effort can be attained from such an insightful and flexible tool.

Link budgets that analyze current operational parameters are necessary before any further research using OPNET is attempted. Also, link analysis that reflects future communication requirements should be made. A best effort case scenario from link analysis is needed before any modifications to the contributed model are made. Otherwise, the model may be dramatically inaccurate and useless.

Modifying the contributed model so that it reflects the concept of operations proposed in this thesis will take several important steps. The mobile nodes in the subnets must have trajectories that reflect typical speed and course for naval ships. Also, the base station is currently static, so it must be converted to be a mobile node. The parameters to set for the attributes of each node within the subnet can then be extrapolated from the link analysis.

Since there are 2 satellites and 2 subnets, duplicating the model and deleting what is unnecessary in a new OPNET project for the initial BG scenario is recommended. After that has been accomplished, an orbit that will cover the BG footprint must be created and then imported into the OPNET model. Satellite Tool Kit (STK) is the best tool for this because OPNET already provides an interface to readily import the orbit into the model.

Once the model is running under the BG link analysis parameters and the STK has been imported to reflect the UAV orbit, statistics generated from OPNET can be compared to the previous analysis. After adjusting the model to reflect the devices and environment, the model can be developed further to simulate or assess the use of various applications, protocols, and internetworking with other UAV networks (sea, land, air).

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BIBLIOGRAPHY

[BAN01] Banks, J., Carson II, J. S., Nelson, B. L., Nicol, D. M., Discrete-Event System Simulation, 3rd Ed. Upper Saddle River: Prentice Hall, 2001

[Bud 00] Buddenberg, Rex. *The Impending Revolution in At-Sea Communications*. Naval Postgraduate School: Monterey, 2001.

[COH00] Cohen, William S. and Henry H. Shelton. Joint Statement on the Kosovo After Action Review, 2000.

[DRE99] Drezner, Jeffrey A. Innovative management in the DARPA high altitude endurance unmanned aerial vehicle program : phase II experience, Santa Monica, CA : RAND, 1999.

[FAS01] "Unmanned Aerial Vehicles." Federation of American Scientists. <http://www.fas.org/irp/program/collect/uav.htm>. , 2001.

[FER01] Ferguson, Charles R. and Douglas A. Harbold. High altitude long endurance (HALE) platforms for tactical wireless communications and sensor use in military operations. Monterey: Naval Postgraduate School, 2001.

[FIR 02] http://www.firestik.com/Tech_Docs/res-n-band.htm

[JAI91] Jain, Raj, The Art of Computer Systems Performance Analysis Techniques for Experimental Design, Measurement, Simulation, and Modeling. Somerset: Wiley, 1991.

[JAG99] Jaeger, Louis, et al. AIRBORNE COMMUNICATIONS NODE (ACN) DESIGN DEVELOPMENT FOR ANTENNA SYSTEM/EMI MITIGATION SYSTEM. Science Applications International Corporation, 1999.

[JFC00] US Joint Forces Command. Operational requirements document for the UAV TCS. Norfolk: Battlespace, Inc, 2000

[LAX96] Lax, Mark and B. Sutherland. An Extended Role for Unmanned Aerial

vehicles in the Royal Australian Air force. RAAF, Air Power Studies Center, 1996.

[LLO01] Lloyd Wood, George Pavlou, and Barry Evans, University of Surrey, Effects on TCP of Routing Strategies in Satellite Constellations, IEEE Communications Magazine, March 2001

[LOG94] Logicon Tactical and Training Systems. *Understanding Link 16: A Guidebook for New Users*, San Diego, CA: Author, April 1994.

[MAJ99] Majewski, Stephen J. Naval command and control for future UAVs. Monterey: Naval Postgraduate School, 1999.

[MAP02] www.maps.com, 2002.

[NCO01] Navy Warfare Doctrine Command, *Network Centric Operations, A Capstone Concept for Naval Operations in the Information Age*, 2001.

[NWC01] Navy Warfare Doctrine Command. NETWORK CENTRIC OPERATIONS A Capstone concept for Naval Operations in the Information Age, Washington DC, 2001.

[ONR00] Office of Naval Research. Review of ONR's Uninhabited Combat Air Vehicle Program. Washington, D.C.: National Academy Press, 2000.

[OPN00] OPNET, MODELER User Guide 8.0, OPNET Technologies, Inc., 2000.

[OPN02] www.opnet.com, 2002.

[OPN03] Chau, Brian, OPNET Contributed Model, www.opnet.com, 2000.

[OWE 00] Owens, Bill. Lifting the Fog of War. New York: FSG, 2000

[ROD01] Roddy, D., Satellite Communications, New York: McGraw-Hill, 2001

[SAD95] Sadiku, M. N. O., Ilyas, M., Simulation of Local Area Networks, Boca Raton: CRC Press, 1995.

[STA02] Stallings, W., Wireless Communications and Networks, Upper Saddle River: Prentice Hall, 2002.

[THO 95] Thomson, Allen. "Civil Satellite Vulnerability." Space News: 20-26 February 1995.

[TOM01] Tomasi, W., Electronic Communications Systems Fundamentals Through Advanced, 4th Ed., Upper Saddle River: Prentice Hall, 2001

[USA01] US Air Force Fact Sheet www.af.mil/news.factsheets/predator

[USAF98] United States Air Force Materiel Command, Globalhawk System Overview, 1998.

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